MARCH, 1937
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The Journal of The Royal Aeronautical Society

With which is incorporated The Institution of Aeronautical Engineers

Edited for the Council by Capt. J. LAURENCE PRITCHARD, Hon. Fellow

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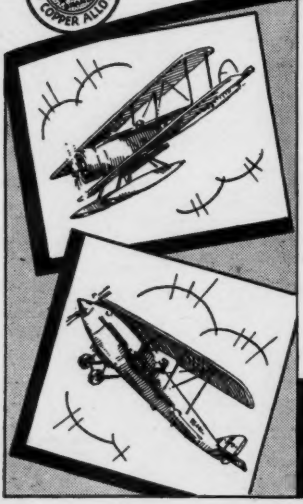

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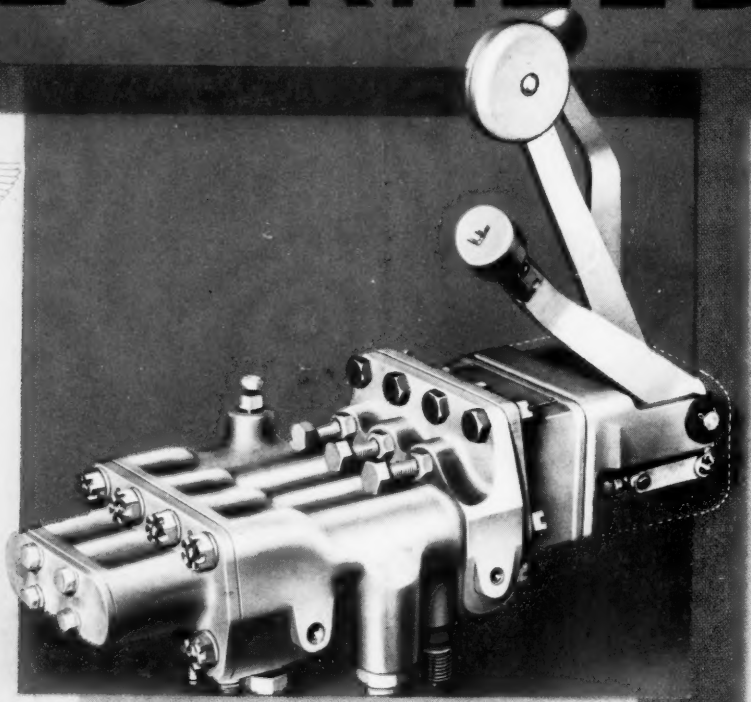

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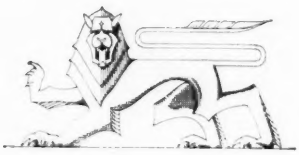

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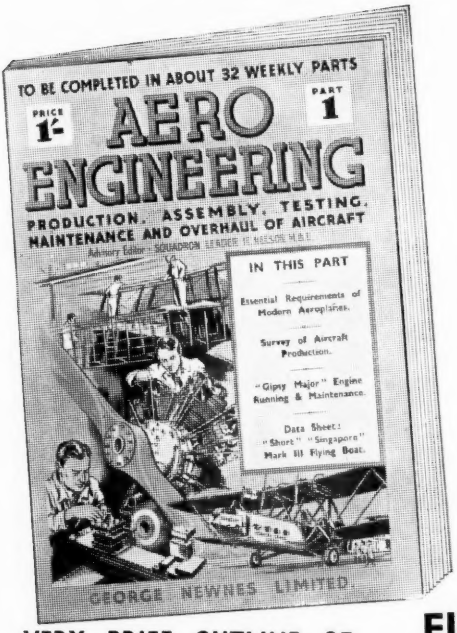
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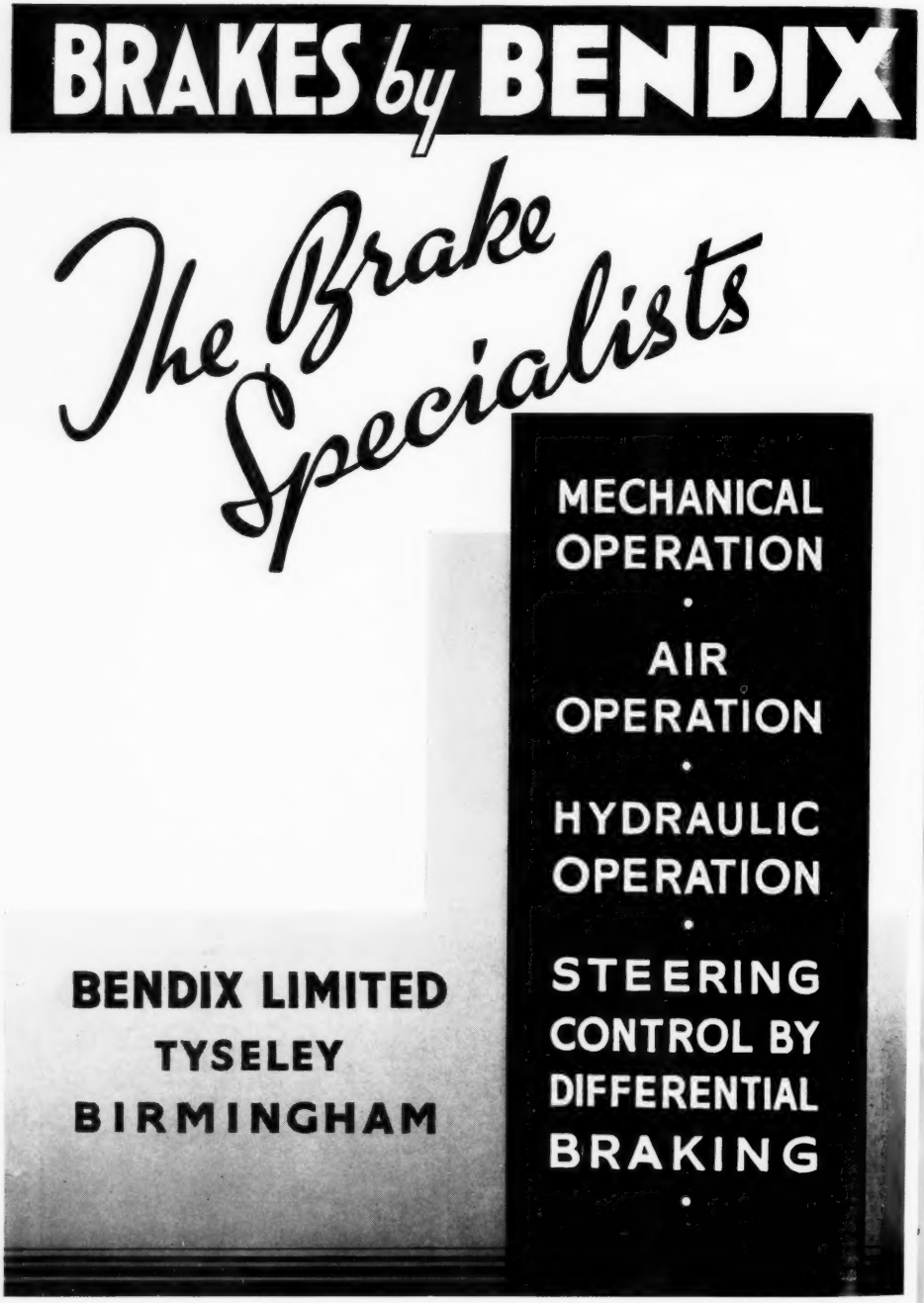
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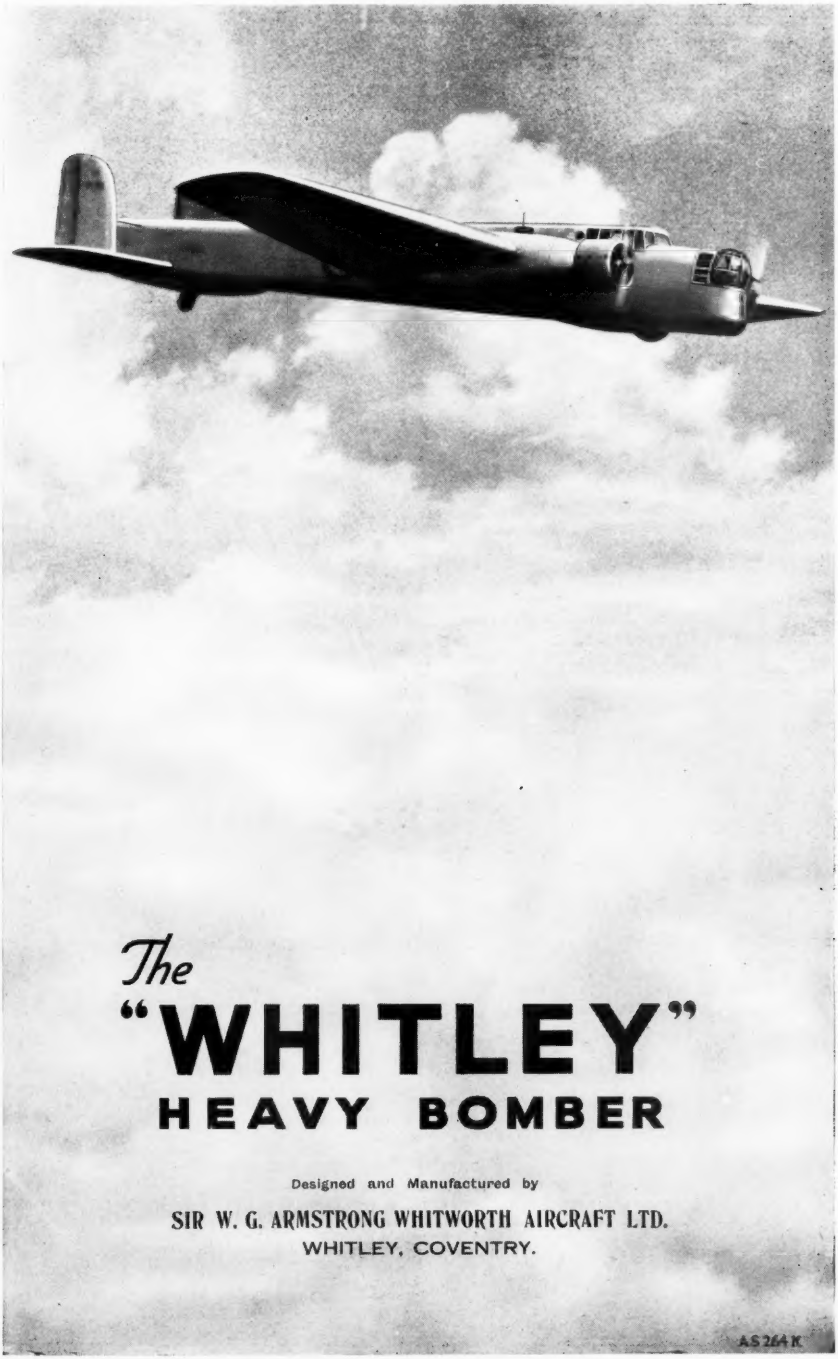
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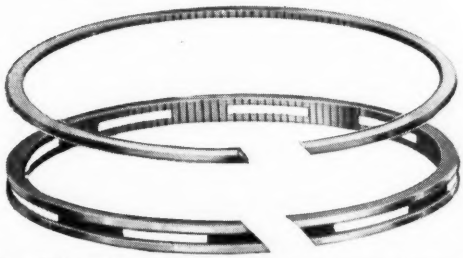

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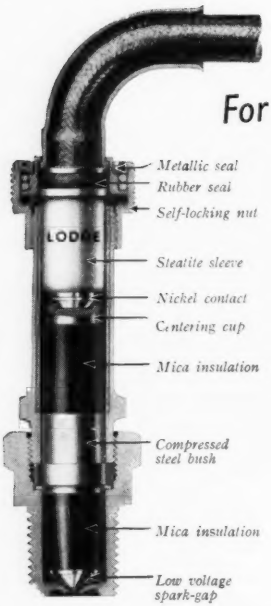

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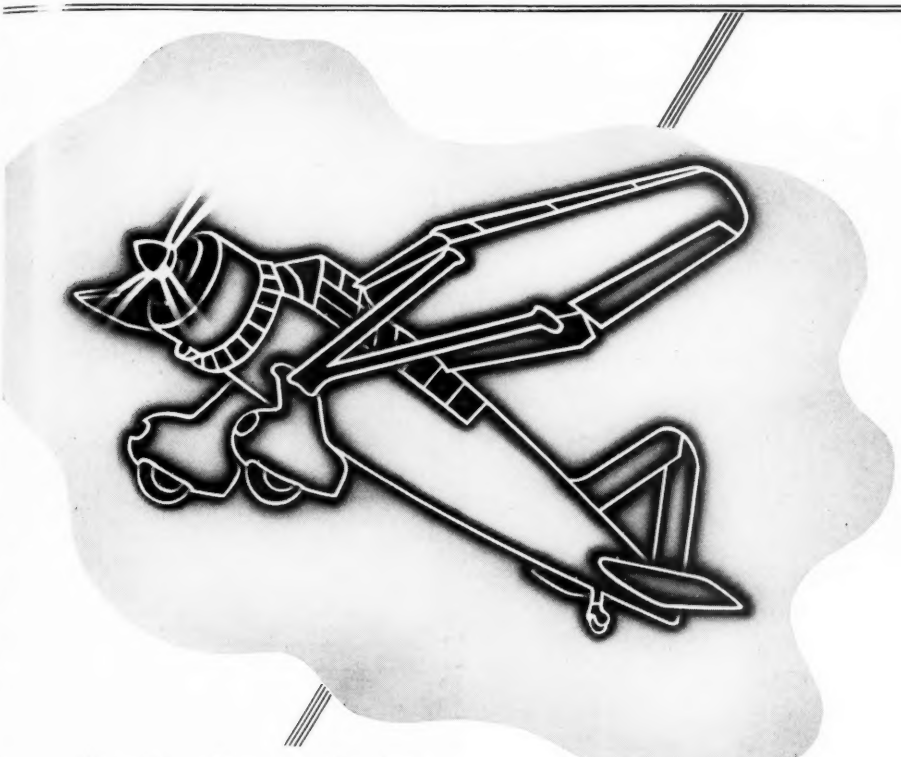

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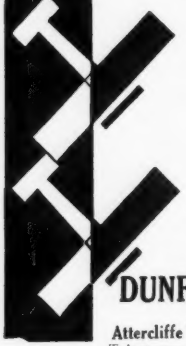

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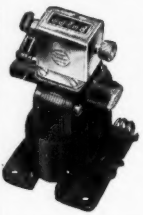

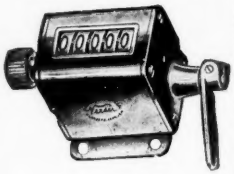

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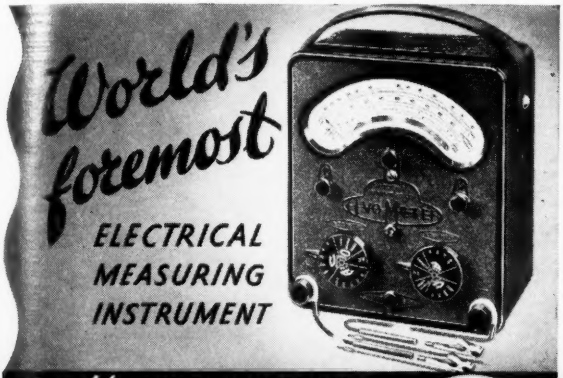

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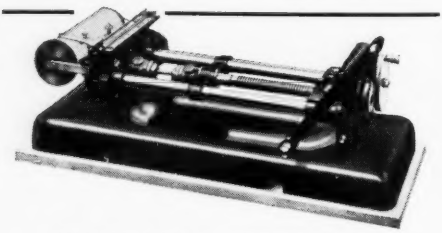

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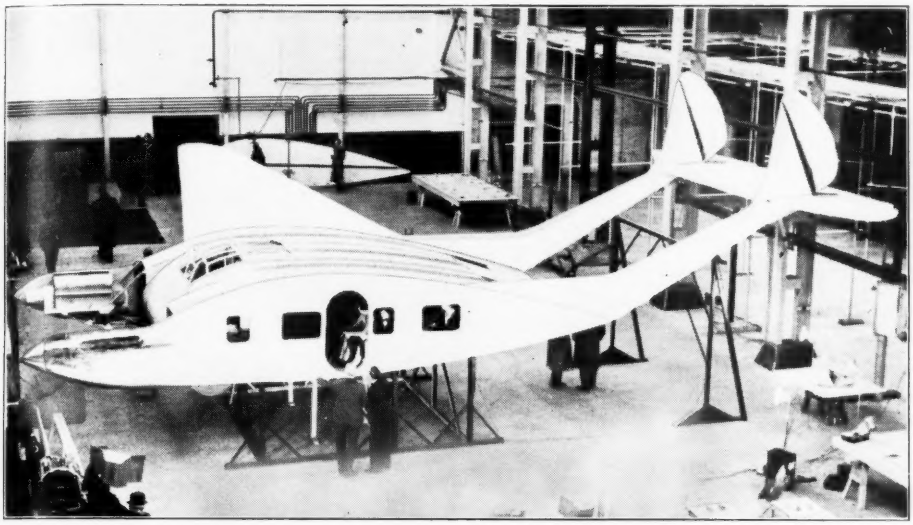

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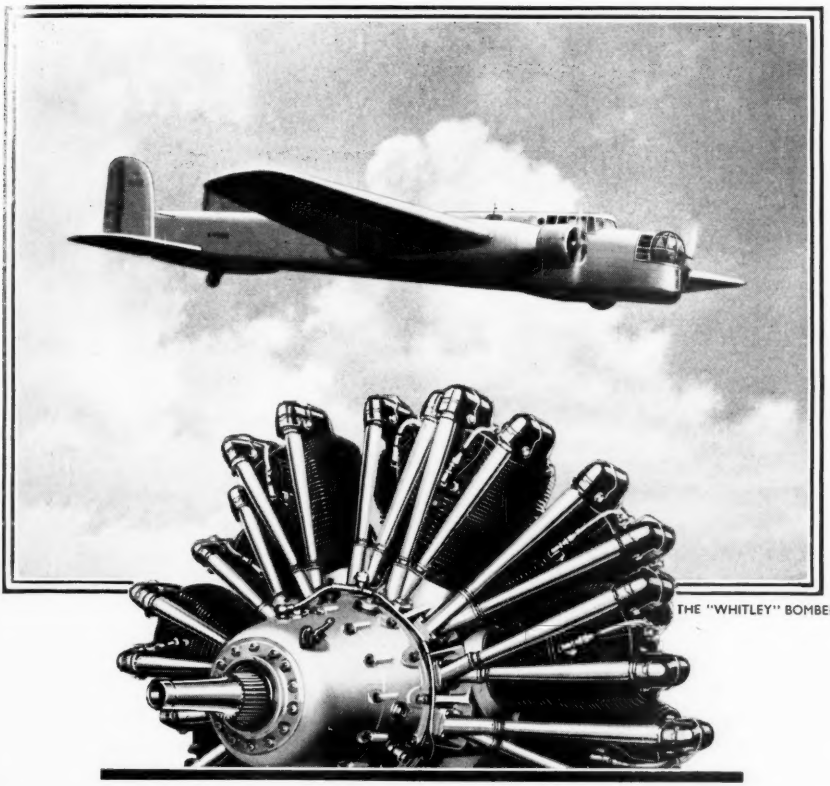

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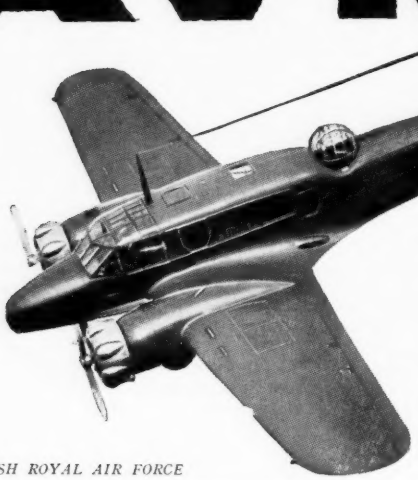

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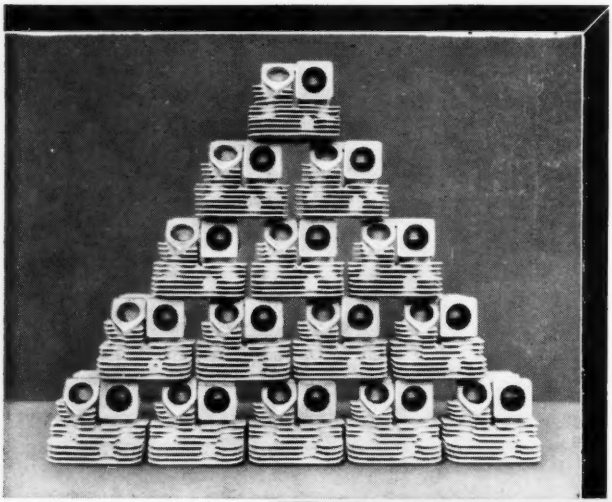

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PROCEEDINGS.

The Royal Aeronautical Society held the first meeting of its 1936-37 Session in the Lecture Hall of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2, on Thursday, October 8th, 1936. The retiring President (Lieut.-Colonel J. T. C. Moore-Brabazon) occupied the chair at the commencement of the meeting.

INSTALLATION OF NEW PRESIDENT.

Lieut.-Colonel J. T. C. MOORE-BRABAZON, M.C., F.R.Ae.S., M.P.: Before vacating the chair, he first took the opportunity to express his appreciation of the kindness extended to him during his two years of office. All good things, he said, came to an end, and the occasion was positively the last on which he would occupy the chair as President. He experienced some regret, because no longer would he be able, from his point of vantage, to gaze at serried ranks of some of the finest brains in England—the owners of some of them having closed eyes, the more to understand the points made by the lecturers! However, he wished to acknowledge how much he had enjoyed his period of office as President. The meetings had not been unduly ruly and he could not remember having to throw anybody out (unlike some political meetings); he appreciated very much the support and kindness shown to him by the Council. A Society was often very much dependent upon one man, who held his office continuously, *i.e.*, the Secretary, Captain Pritchard, to whom all connected with the Society owed an enormous debt of gratitude; Colonel Moore-Brabazon expressed his own personal gratitude for the kindly way in which Captain Pritchard had piloted him through certain difficulties which had arisen from time to time.

Introducing his successor, Colonel Moore-Brabazon said that although in the past there might have been in the minds of retiring Presidents some misgivings as to the future of the Society, owing to the choice of the succeeding Presidents (and no doubt his own predecessor, Mr. C. R. Fairey, must have experienced such misgivings, but, with true courtesy, had never allowed anyone to become aware of them!), on the present occasion no one could experience such feelings, for the new President, chosen by the Council, was Mr. H. E. Wimperis (applause). It would be quite unnecessary, before such a meeting, to detail his scientific attainments, but the Society must record the fact that for many years he had been a member of the Aeronautical Research Committee, and, of course, he had been Director of Scientific Research at the Air Ministry for a long time. Mr. Wimperis had many initials after his name, indicating his qualifications, and they showed the world that he was very clever; but they did not mean necessarily that he was wise! Long association with him, however, demonstrated that he was a very wise man as well as a clever man, and he was one of the greatest and keenest friends the Royal Aeronautical Society had ever had. His devoted work over a period of many years, both from the point of view of the Council and from the point of view of the relationship between the Air Ministry and the Royal Aeronautical Society, had been of immense value, and the Society would always be indebted to him for it. There was no one to whom the reins of the Society could be handed with more confidence than to Mr. Wimperis. The members of the Council had learned to respect him, to admire him and to love him, and Colonel Moore-Brabazon wished him as happy a period of office as he himself had enjoyed.

Mr. H. E. Wimperis, who was received with prolonged applause, formally occupied the chair.

The PRESIDENT: He first took the opportunity to express to Colonel Moore-Brabazon the Society's gratitude for his great services as President during the last two years. He recalled that Elijah, when taking his flying chariot upwards, had left behind him a cloak, and said he hoped that the cloak of Colonel Moore-Brabazon would fall upon him just as Elijah's cloak had fallen upon Elisha. The cloak which had fallen upon Elisha had worked miracles, and Mr. Wimperis felt that nothing short of some such miraculous intervention would enable him to follow as he would like to do in the steps of his distinguished predecessor.

A real debt of gratitude was due to Colonel Moore-Brabazon for having steered the Society during the last two years. It could not have been easy for him because he was also a Member of Parliament, and it had been necessary for him to combine two very different kinds of functions. But what the High Court of Parliament might have lost had been very much the Society's gain, and the services he had rendered as President of the Society had been of very real help to the community, to the country at large. He had been associated with flying in a very practical way for a longer period than perhaps anyone else in the meeting room; his record was known and it was unnecessary to dilate upon it. But in the name of all the members of the Society he desired to say to Colonel Moore-Brabazon that they were exceedingly indebted to him, and they hoped that he would continue to give the Society the benefit of his counsel and advice Mr. Wimperis proposed a hearty vote of thanks to him for his distinguished services.

(The vote of thanks was carried with hearty acclamation).

The PRESIDENT: Dr. Lachmann's name was well known, by reason of his work in aeronautics. He carried certain German decorations of a very distinguished kind, among them the " Iron Cross " (First Class). He was a Fellow of the Society and had been one of the technical staff of Messrs. Handley Page, Ltd., for the last seven years. During the war he was a pilot; since then he had served in aerodynamic research work at Göttingen for three years, as chief designer to the Albatross Company for a year, and as technical adviser to a Japanese works for three years. The subject of the aerodynamic and structural features of tapered wings was one to which he had given a great deal of personal attention. The difficulty of the subject could be judged by the fact that those of our fellow creatures, who had been studying the subject for the last million years, were still unable to make up their minds about it; some birds had tapered wings and some had not!

AERODYNAMIC AND STRUCTURAL FEATURES OF TAPERED WINGS.

By G. V. LACHMANN, Dr. Ing., F.R.Ae.S.

During the last four or five years a remarkable evolution has taken place in the policy of aircraft design. Its ultimate aim is to reduce the aeroplane to the simplest possible form offering the least resistance to the air. This process of eliminating any structural members which are not necessary for the production of lift and the housing of passengers or military load has automatically led to the adaptation of the fully cantilever monoplane with retractable undercarriage (Fig. 1). The final logical result of this evolution is, of course, the flying wing with the engines, passengers or military load housed inside, thus suppressing such components like the fuselage and the tail unit which at the moment are still causing a non-productive addition to the total drag. There are still certain difficulties which will prevent us from achieving the ideal of, say, a mere flying

wing, and our present compromise solution consisting of a tapered cantilever wing, a streamlined fuselage and a cantilever tail unit will probably persist for some time to come. The next step in suppressing parasitic drag will, therefore, consist in a still greater refinement of fuselage design and in eliminating outside engine nacelles by using engines buried inside the wing.

In times of rapid technical development there will always exist a lag between technical problems and theoretical and experimental analysis. During the last few years extensive research has dealt with many aspects of monoplane construction, but I am not minimising the efforts and the results of this work by stating that some four or five years ago the designer of cantilever monoplanes was left to his own judgment and intuition on many important questions of design.

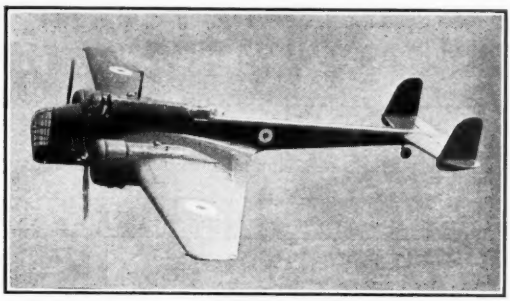

FIG. 1.

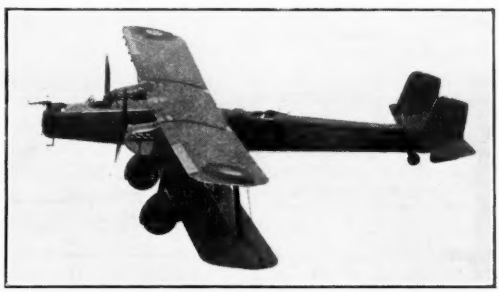

FIG. 1A.

These problems were mainly those concerned with aerodynamic and structural features of cantilever tapered wings, because it was the wings which were mainly affected by the new design policy.

I should like to make it quite clear that I am fully aware of the fact that a paper on this complex subject to be given at this stage can only be piece work; our knowledge is still very incomplete and certain gaps have to be filled in by future research, but I feel that even at this stage a stocktaking of our present knowledge is useful. As there are still quite a variety of views held by various designers on certain subjects connected with tapered wings, I hope that a paper presented in a somewhat one-sided way, according to the design policy which I followed, will challenge other views and result in a productive discussion.

I.

Some Fundamental Characteristics of the Fully Cantilever Tapered Wing.

The modern monoplane is not a result of superior aerodynamic characteristics of the tapered wing. Whilst rectangular wings of constant thickness are the most rational solution for a braced biplane, wings tapered in plan form and in thickness are the most rational solution for a cantilever monoplane. Here the bending moment due to the air load on the wings reaches a maximum at the wing root and falls off rapidly towards the tips, whereas in a biplane girder it is resolved in concentrated column loads (compression or tension) in the spars of upper and lower wing with superimposed relatively small secondary bending moments.

In the case of ordinary biplane wings the design variables were area, span and wing section, and there was generally little choice left to the designer. In

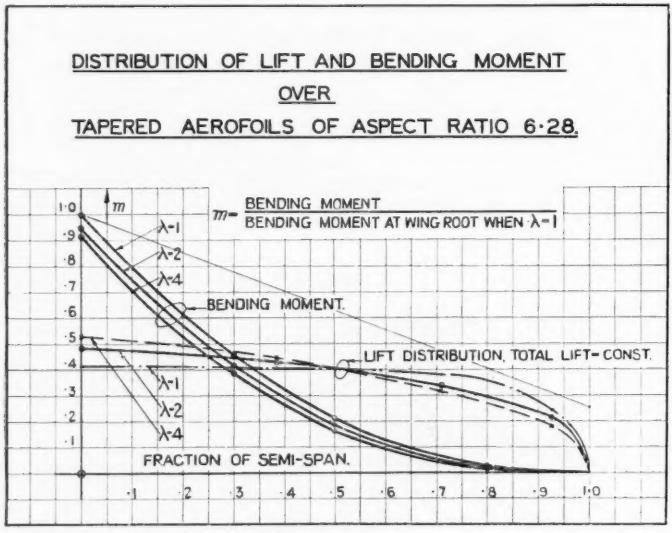

Fig. 2.

the case of a cantilever wing, new variables make the design problem a little more complex. The new variables are taper ratio and distribution of thickness and of wing section along the span.

I should like to deal first with some fundamental structural effects of the taper ratio which is usually determined by the ratio of tip chord to root chord. I prefer the ratio of root to tip chord in the following discussions.

1. Taper Ratio and Spar Flange Weight.

In Fig. 2 the distribution of lift across the span has been plotted for a rectangular wing and for wings of various taper ratios, all of the same aspect ratio of 6.28. It becomes apparent from this diagram that as the taper ratio increases the air load on the wing is more concentrated towards the wing root and falls off towards the tips.

Correspondingly the bending moments, also plotted in Fig. 2, are reduced as the taper ratio increases. Although the reduction in bending moment is definitely marked, the difference is not sufficiently significant to explain the superiority of a tapered monoplane wing over a rectangular monoplane wing from the point of view of structural economy. If the bending moment is divided at any point of the wing span by the available height of the spars or the distance between top and bottom skin respectively and if a certain constant mean stress is assumed, this ratio represents a measure of the material required either in the spar flanges or in the stressed skin replacing the latter.

If we denote with:—

a_x = thickness/chord ratio at locus x.
BM_x = bending moment.
c_x = chord at locus xs.
c_{mean} = mean chord = $Sw/2s$.
S_w = total wing area.
s = semi-span.
c_o = root chord.
λ = taper ratio.
f_x = measure of flange area = $BM_x/a_x \,.\, c_x$

$$= BM_x/a_x c_{mean} \,[\,2\,\lambda/(1+\lambda) - 2x\,(\lambda-1)/(1+\lambda)\,].$$

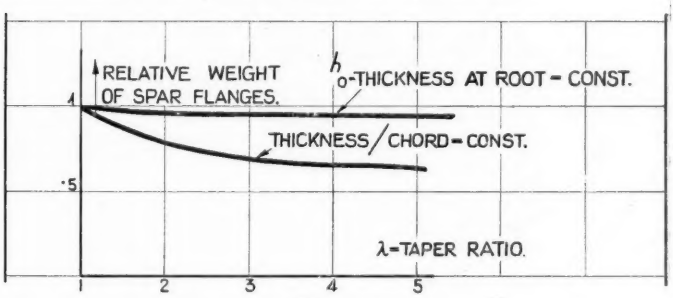

FIG. 3.

By plotting f_x over the span and by integrating the areas determined by the axis and the curves for f_x, a measure w is obtained for the material required to deal with the bending moments.

$$w = (1/c_{mean}) \int_0^1 \{\, BM_x/a_x \,[\,2\,\lambda/(1+\lambda) - 2\,x\,(\lambda-1)/(1+\lambda)\,]\,\}\, dx.$$

Fig. 3 contains the results of the integration indicating how the weight of the spar flanges or the stressed skin replacing the spar flanges is diminished as the taper ratio increases.

2. TAPER RATIO AND MEAN PROFILE DRAG.

This comparison emphasises the weight point of view. Alternatively, one can take the following viewpoint. Assuming that profile thickness affects profile drag in a decisive way the mean resulting thickness chord ratio of a tapered wing for a given absolute profile thickness of the wing root will decrease as the taper ratio increases. If

a_o = thickness chord ratio of wing section at the root,
a_t = thickness chord ratio of the wing section at tip,
$a_o/a_t = n$,

the thickness of a section at the locus x will be

$$h_x = h_o\,(1 - ax)$$

where

$$a = 1 - 1/n\lambda.$$

Hence

$$(h/c)_{\text{mean}} = h_o/c_{\text{mean}} \int_0^1 \{\,(1-ax)/c_x\,\}\, c_x \,.\, dx = (h_o/c_{\text{mean}})\,(1 - a/2).$$

Values of $(h/c)_{\text{mean}}$ as a function of the taper ratio for wings with constant height at the root and a varying degree of thickness/chord ratio from root to tip are plotted in Fig. 4. The corresponding expressions for flange weight are represented in Fig. 3, indicating a smaller degree of weight reduction with increase of taper ratio than that followed from the first comparison.

It follows from Fig. 3 that there is little point in adopting taper ratios greater than 4 in order to keep the mean thickness/chord ratio of the wing low.

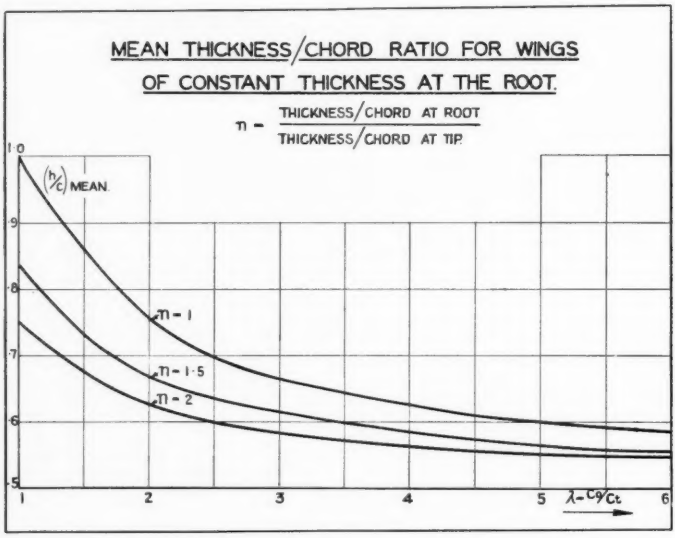

FIG. 4.

I consider the second comparison where the emphasis is laid on minimum profile drag as less conclusive than the first one in view of our uncertain knowledge of the influence of scale effect on profile drag. According to wind tunnel evidence (1) profile drag is fairly proportional to the thickness/chord ratio, but certain tests at high Reynolds number seem to indicate that up to a certain relatively large thickness/chord ratio (18 per cent.) the effect of form drag is negligible and that all the drag can be traced back to pure skin friction. It may be, however, that at very high flying speeds where compressibility becomes noticeable the picture may change again. Further research on full-scale profile drag and on the effect of thickness/chord ratio will influence materially future design policy.

3 SKIN WEIGHT AS AFFECTED BY TAPER RATIO.

For a skin covered wing of constant thickness chord ratio relatively simple expressions can be derived (on the basis of the well known Bredt/Batho formulæ)

for the distribution of torque and skin thickness along the span, the resulting weight of the skin and the torsional deflection at the tip. The effect of end constraints is not considered, but it is appreciated that additional bending moments near the root of a highly tapered wing may be as much as 20 per cent. greater than those occurring in a wing of constant chord and thickness.

In regard to the shear stress due to torque it is assumed that this stress be constant, *i.e.*, the skin thickness is assumed to be thinned down along the span proportionate to the decrease of torque divided by the enclosed area. This assumption agrees fairly well with current structural practice, besides, it can be shown theoretically that this assumption leads to maximum stiffness or minimum strain energy (2).

With those assumptions the torque T_x at any position x of the semi-span becomes

$$T_x \sim \int_x^s c^2 dx, \text{ provided } \rho v^2 \text{ and } Cm = \text{const.}$$

The minimum thickness t_x required at any point x from the tip is

$$t_x = T_x / 2\,A \,.\, f_s$$

where A = enclosed area of shell $\sim c_x^2$.

f_s = shear stress = const.

Hence

$$t_x \sim (1/c_x^2) \int_x^s c^2 dx.$$

Minimum weight of skin

$$w_s \sim \int_0^s c \,.\, t \,.\, dx$$

as P = perimeter of section $\sim c$.

Angle of twist at the tip

$$\Theta = \int_0^s (T_x / G I_D)\, dx$$

where

$$I_D = (4\,A^2 \,.\, t/P) \sim c^3 \,.\, t.$$

Hence

$$\Theta \sim \int_0^s (1/c)\, dx.$$

The solutions of the integrals for w_s and Θ on the basis of constant wing surface are :—

$$w_s \sim \{\ \Lambda^{\frac{1}{2}} s_w^{3/2} / 18\,(\lambda+1)\,(\lambda-1)^2\ \}\ [\lambda^3 - (1 + 3\log_e \lambda)]$$

$$\Theta \sim (\Lambda/4)\ \{\ (\lambda+1)/(\lambda-1)\ \}\ \log_e \lambda$$

where Λ = aspect ratio $= 4\,s^2/S_w$.

The decisive design criterion for cantilever wings which determines critical flutter speed and aileron reversal speed is the torque stiffness.

The most efficient structure will then be determined by the least torsional deflection obtained with the least amount of skin material. As a figure of merit for comparison the ratio $1/(w_s \,.\, \Theta)$ has been chosen.

w_s, Θ and the ratio $\eta = 1/(w_s \,.\, \Theta)$ are plotted in Fig. 5 as a function of taper ratio with aspect ratio as a parameter. Independent of aspect ratio η reaches

an optimum for taper ratios of 4 to 5. High taper ratios seem to offer, therefore, definite structural advantages from the point of view of strength in bending and torsional stiffness. There are, of course, also secondary considerations in favour of a large root chord and a maximum of structural height, namely, the possibility to stow away large petrol tanks, bombs, retractile undercarriage, etc.

However, this purely structural viewpoint has to be tempered by a consideration of the aerodynamical characteristics as effected by the taper ratio, and here the effect is not always favourable unless special precautions are taken. Attempts have been made to determine the " optimum " taper ratio, embracing both the structural and aerodynamic effects, but the variables are so manifold and

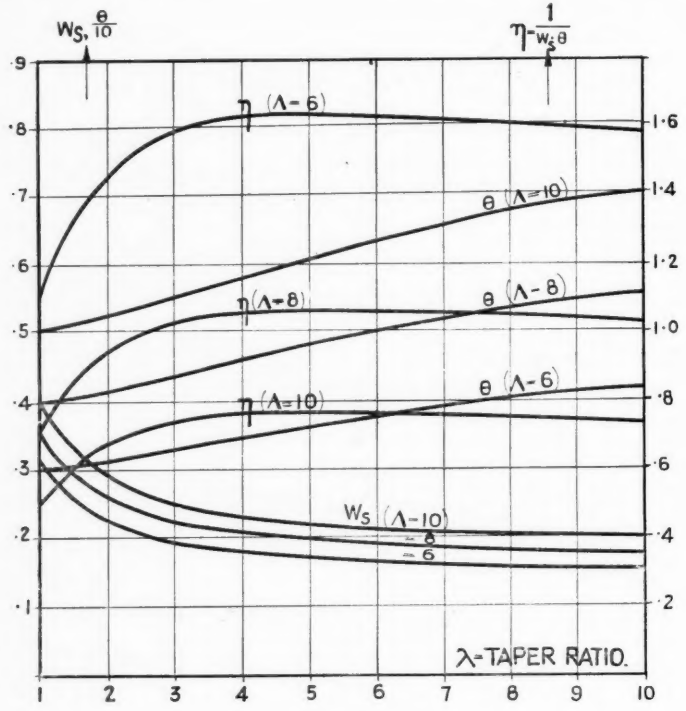

FIG. 5.

indefinable that I consider it a futile attempt to obtain a rational solution expressed by a mathematical formula.

This difficulty is reflected in the wide variety of taper ratios employed by different designers, but there seems to be a growing tendency towards the use of higher taper ratios in view of the obvious structural advantages.

II.

SOME IMPORTANT AERODYNAMIC CHARACTERISTICS OF TAPERED WINGS.

In the following I propose to describe in which way certain important aerodynamic characteristics of tapered wings are affected by the taper ratio.

1. Lift Distribution.

The designer and stress engineer dealing with tapered wings owes a great deal to the late Mr. Glauert (3) who originated a fairly simple and straightforward method for calculating the lift distribution for a wing of a given regular plan form. The fundamental solution of the problem is, of course, based on the Lanchester-Prandtl theory which supplies the law according to which lift and induced velocity across the span are interconnected. If we denote with α_g the geometric angle of incidence of any aerofoil element, and if w represents the value of induced velocity at this point, then the effective angle of incidence α_e of this aerofoil element will be

$$\alpha_e = \alpha_g - w/v.$$

Lift and induced velocity at any point y_1 of the span are interconnected according to Prandtl by the function :—

$$w(y_1) = (v/8\pi) \int_{-s}^{+s} \{ d(C_L C/dy)\, dy \} /(y_1 - y) \quad . \quad . \quad . \quad (1)$$

The simple method of solving this integral is due to Glauert, who expressed the lift across the span by a Fourier series. The method is well known and requires no further description. A more recent method developed by Miss J. Lotz (4) on a similar basis requires less time in its application at greater accuracy. Apart from these purely analytical methods there have been developed a number of graphical methods which are particularly useful in such cases where the analytical method breaks down, due to local singularities, for example, in the case of a partly stalled wing or in the case of a wing where a sudden change in the aerodynamic characteristics takes place. All these graphical methods are based on the principle of step by step approximations. One assumes in first approximation a plausible distribution of lift and calculates the downwash velocities at various points of the span according to (1).

Having found the downwash velocity the effective angle at each point of the span is known and taking into account the lift curve of the section at this point one can determine the local lift coefficient $C_L = (dC_L/d\alpha)\,\alpha_e$. In order to satisfy the aerofoil theory and in order to make the assumed lift distribution into the actual one, the local lift coefficients thus obtained should check up with the assumption. This is, of course, usually not the case, and therefore further approximations have to be made until the original lift and the check lift agree. Graphical methods have been developed by Fage (5), Jurieff (6), Tani (7) and Lippisch.

While in the days of biplane construction the lift distribution across the span was a fairly simple matter fixed by certain standard asumptions, the designer of tapered wings has to pay much greater attention to the actual lift distribution for the individual plan form chosen by him.

Figs. 6 and 7 show how the distribution of C_L, α_e (effective angle of incidence) lift and induced velocities are affected by various typical plan forms. An elliptical wing giving minimum induced drag for a given span and a given total lift has a constant value of C_L across the span and a constant induced velocity at each point of the span. A rectangular wing shows an increase of induced velocity towards the tips and correspondingly a fall off of C_L and effective angle towards the tips. On a tapered wing the induced velocities first fall off towards the tips and increase again right at the tips. On a triangular wing there is actually an up wash at the outer tips resulting in very high C_L values near the tips.

2. Mean Aerodynamic Chord of Untwisted Tapered Wings.

In connection with lift distribution across the span of a tapered wing I should like to say a few words about the aerodynamic mean chord of a tapered wing.

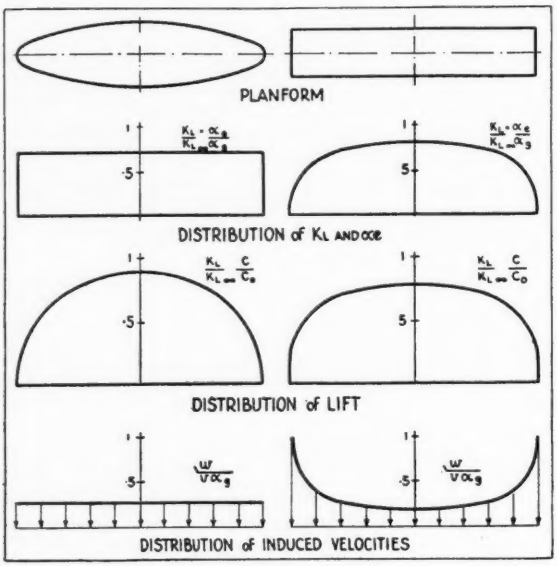
PLANFORM
DISTRIBUTION of K_L AND α_e
DISTRIBUTION of LIFT
DISTRIBUTION of INDUCED VELOCITIES

FIG. 6.

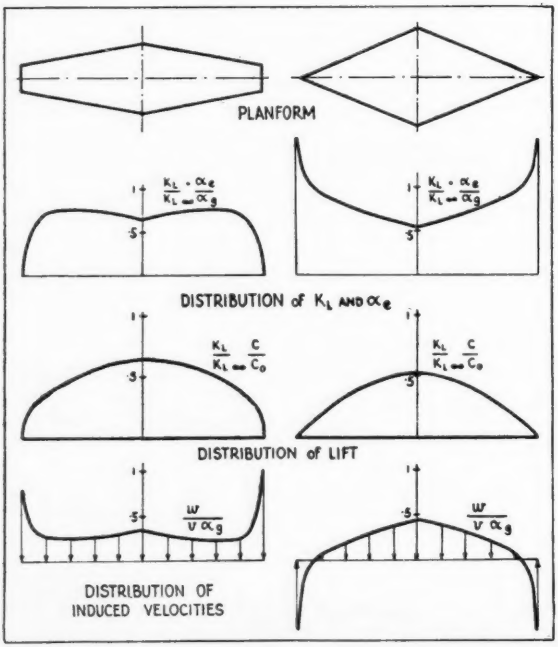
PLANFORM
DISTRIBUTION of K_L AND α_e
DISTRIBUTION of LIFT
DISTRIBUTION OF
INDUCED VELOCITIES

FIG. 7.

The conception of aerodynamic mean chord has been found very helpful in determining the balancing loads for a new design and also in comparing the relative C.G. positions of aeroplanes of varying plan form. It can also be utilised for estimating the effect of sweepback on pitching moments. By introducing the conception of an aerodynamic mean chord the tapered wing can be reduced to an equivalent wing of constant chord c_{mean} (Fig. 8) and the moment about the leading edge of this wing can be expressed in the simple way :—

$$M = C_{mo} + 0.25\ (dC_L/d\alpha)\ c_{mean}\ (\rho v^2/2)\ S_w$$

where C_{mo} = zero lift moment, c_{mean} = aerodynamic mean chord, S_w = area of tapered wing.

The aerodynamic mean centre (AMC) is assumed to be constant at 0.25 of the chord. In order to find the equivalent rectangular wing and its position relatively to the actual tapered wing, it is necessary to determine the lateral and longitudinal co-ordinates Y, X of the aerodynamic mean centre of the tapered wing and the length of the aerodynamic mean chord. The location of the AMC which is defined as that point on the wing about which at constant ρv^2 the resultant air force is constant at all angles of attack is given by :—

$$y = \{ \int_0^s C_n \,.\, c \,.\, y \,.\, dy \} \,/\, \{ \int_0^s C_n c\, dy \}$$

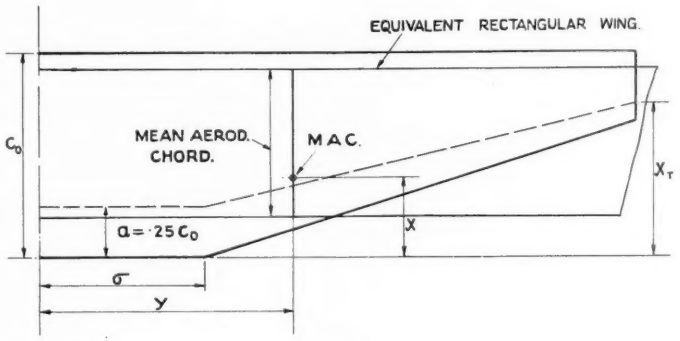

FIG. 8.

and

$$x = \{ \int_0^s C_n c x\, dy \} \,/\, \{ \int_0^s C_n c\, dy \}$$

The aerodynamic mean chord is determined by the following expression :—

$$c_{mean} = (\int_0^s c^2 dy)/(\int_0^s c\, dy).$$

These three expressions can be evaluated graphically. For untwisted trapezoidal wings or wings composed of a rectangular centre portion and trapezoidal outer wings which are in common use nowadays and also for elliptical plan forms, my assistant J. R. Crean (8) has found an analytical solution resulting in a very simple formulæ.

1. *Length of Mean Aerodynamic Chord.*

$$= (2/3)\, c_0\, [(\lambda_1^2 + \lambda_1 + 1) - \sigma\,(\lambda_1^2 + \lambda_1 - 2)]/[(\lambda_1 + 1) - \sigma\,(\lambda_1 - 1)]$$

where

$$\lambda_1 = \text{ratio } \frac{\text{tip chord}: c_t}{\text{root chord}: c_0} = 1/\lambda.$$

σ = fraction of semi-span over which the wing is rectangular in plan form; zero for a simple tapered wing.

2. *Co-ordinates of Mean Aerodynamic Centre.*

Lateral co-ord. $Y = 0.425\, s$ . . . . . (i)

Longitudinal co-ord. $X = \frac{1}{4}\,(A + a)\;\; c_0 + (1 - A + a)\, X_T$ . . (ii)

where s = semi-span.

X_T = ordinate of quarter point locus at wing tip measured from a datum perpendicular to the root chord C_0 and passing through its leading edge.

A and a are functions of σ whose values are tabulated below.

The formulæ (i) and (ii) above are strictly applicable only in the case of an elliptical lift distribution; however, since in most cases in practice the loading approaches very closely to that type, the formulæ quoted are almost always sufficiently accurate. More general expressions are given in Ref. 8.

σ	A	a
0	1	−0.4245
0.05	1.0492	−0.4452
0.10	1.0972	−0.4644
0.15	1.1428	−0.4824
0.20	1.1872	−0.4988
0.25	1.2280	−0.5132
0.30	1.2668	−0.5260
0.35	1.3032	−0.5368
0.40	1.3360	−0.5444
0.45	1.3664	−0.5496
0.50	1.3916	−0.5512
0.55	1.4116	−0.5496
0.60	1.4272	−0.5432
0.65	1.4368	−0.5324
0.70	1.4388	−0.5152
0.75	1.4332	−0.4916
0.80	1.4164	−0.4584
0.85	1.3880	−0.4136
0.90	1.3368	−0.3518
0.95	1.2532	−0.2586

These formulæ are based on the assumption that the wing is untwisted, and that the lift distribution itself is not affected by sweepback.

Within the practical limits of sweepback generally used, this assumption should be accurate enough to justify the application of the formulæ to evaluate quickly the effect of sweepback on equilibrium. If $\Delta_x = X_{T2} - X_{T1}$ represent the amount by which the tip chord is moved aft, the corresponding shift of the AMC is found from the expression:—

$$(X_2 - X_1)/c_0 = (\Delta X/c_0)\, [1 - (A + a)].$$

In this way the amount of sweepback can be calculated which is necessary to offset a certain shift of C.G. This simple method is particularly useful when balancing up a new design.

As already mentioned the basic assumption has been that the wing is untwisted. A twisted wing has no aerodynamic mean centre because the shape of the loading curve differs for each angle of attack, and there is no single point about which

the moment of the resultant force will remain constant and invariant of angles of attack.

The pitching moment of twisted tapered wings has been dealt with in a paper by Glauert and Gates (9), also recently by Raymond F. Anderson (10).

3. Damping in Roll and Aileron Efficiency.

The rolling moment due to roll for a wing having a constant positive value of $dC_L/d\alpha$ (below the stall) can be expressed by

$$L_p = \int_{-s}^{+s} (\rho v^2/2)\,(dC_L/d\alpha)_\infty \,.\, f_m\,(p\,.\,x/v)\;\; c_x\,.\,dx$$

where f_m = downwash factor according to Munk, dependent on lift distribution and aspect ratio, p = rate of roll, c_x = chord at distance x from the centre line. The value of this integral for a trapezoidal wing with root chord c_0 and tip chord c_t becomes

$$L_p = KD\,.\,\rho/2\,.\,v\,.\,p$$

where

$$KD = \int_{-s}^{+s} (dC_L/d\alpha)_\infty \,.\, f_m \,.\, S_w\,(s^2/3)\,\{\,1 - 0.5\;\;(1 - c_t/c_0)/(1 + c_t/c_0)\,\}\,.$$

The value of KD has been plotted in Fig. 9 as a function of aspect ratio with varying taper ratios as parameter. There is a pronounced falling off in the value of KD as the taper ratio increases.

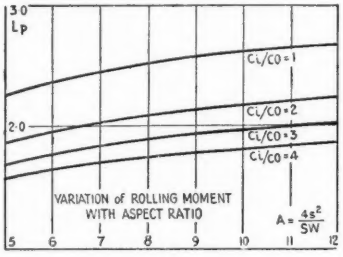

Fig. 9.

If we denote with L_r the rolling moment produced by a certain aileron setting and if B = moment of inertia about the longitudinal axis

$$A\,.\,\dot{p} + KD\,.\,p = L_r.$$

It can be shown that the effect of A is negligibly small and that after a short interval uniform rotation is established. Neglecting the influence of moment of inertia we find $p_\infty = L_r/KD$. This ratio can be considered as a criterion for the aileron efficiency. For a given aspect ratio L_r, *i.e.*, rolling moment due to the ailerons, depends on the aileron angle, the area of the ailerons and the aileron span. Ailerons with constant chord have been found somewhat superior to ailerons with constant chord ratio, but Mathias (11) has shown that for usual aileron proportions L_r is approximately :—

$$L_r \sim [\sqrt{\{\,S_a/S_w\,(1 - si/s)\,\}}\,]\,[1 - (si/s)^2]$$

where S_a = aileron area, S_w = wing area, si = distance of inboard aileron chord to centre line, s = semi-span. For a given ratio of aileron area to wing area it can be easily verified by differentiating this expression that for a given aileron

area the optimum aileron span is two-thirds of the semi-span,* a fact which is well borne out by practical experience.

On the approximate assumption that for a given ratio of aileron area to wing area and for a given aileron span and aileron setting, the rolling moment produced by the ailerons is invariant of the taper ratio, it becomes obvious that the rate of roll produced is indirectly proportional to KD and the reciprocal values of KD therefore represent a criterion for aileron efficiency. On this basis the rate of roll for a tapered wing of taper ratio 4 is about 39 per cent. larger than p for a rectangular wing.

These theoretical considerations have been confirmed by wind tunnel tests and practical observation, and they explain why tapered monoplanes, especially those of high taper ratios, have shown surprisingly good lateral controllability in flight below the stall. N.A.C.A. Technical Note No. 449 (12) deals with wind tunnel research on lateral control devices fitted to tapered wing. The rolling criterion adopted in this investigation is a figure of merit which was designed to be proportional to the initial accelerations of the wing tips following instantaneous deflection of the ailerons from neutral regardless of the air speed or the plan form of the wing. Expressing in coefficient form this rolling criterion is:—

$$RC = (C_l \cdot S_w \cdot s^2)/(12 \cdot C_L \cdot I_x)$$

where C_l = coefficient of rolling moment due to the ailerons with respect to the body axis.

I_x = area moment of inertia of the wing about the mid-span chord line.

In the American report the numerical value of this criterion representing satisfactory control conditions has been assumed as approximately 0.075. The wings compared were a rectangular wing and two tapered wings of taper ratio 5 : 3 and 5 : 1. Below the stall up to 10° the wing with the highest taper ratio 5 : 1 gave 30 per cent. higher values for the figure of merit than the rectangular wing. The adverse yawing moment and hinge moments were lower than for corresponding ailerons on the rectangular wing and on the wing of low taper ratio. However, just above the stall the rolling moment fell off almost completely and adverse yawing moments of great magnitude occurred on the wing of high taper ratio, while the wing with lower taper ratio gave lower rolling moments than the rectangular wing also with increased yawing moments.

Stability against rolling caused by gusts as defined as loss of damping in roll at a value $ps/v = 0.05$ occurred at angles about 3° lower for either of the tapered wings than for the rectangular wing with 0° yaw. With 20° yaw the limiting angle for the wing with 5 : 3 taper was about the same as that for the rectangular wing, but for the wing with 5 : 1 taper the limiting angle was 3° higher and had the same value as for 0° yaw.

(The value of $ps/v = 0.05$ was chosen, as test flights have shown that in severe gusts a rolling moment of this magnitude may be set up.)

The earlier loss of damping in roll as taper ratio increases has been confirmed by H. B. Irving and A. S. Batson's recent tests at the N.P.L. (13). A rectangular wing and tapered wings of taper ratio 2.5, 4 and 9 were mounted on the rolling balance and rotated at a constant tip speed corresponding to $ps/v = 0.05$. In plotting the rolling moment due to roll, the degree of instability and the angle at which damping in roll disappears could be determined. These angles derived from Irving's tests are plotted in Fig. 10. For wings with no flap and also for wings with 50 and 70 per cent. partial flaps and 100 per cent. flap it is evident that the angle at which damping in roll disappears becomes smaller as the taper ratio increases. The effect is most pronounced for wings fitted with complete flaps.

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* $\partial/\partial(si/s) = [\{1-(si/s)^2\}/\{1-si/s\}] = 0$ $si/s = \frac{1}{3}$

The better response to ailerons and its resulting effect of manœuvrability which is afforded by wings of higher taper ratio can therefore only be utilised if care is taken to maintain a sufficient degree of lateral control at and beyond the stall.

4. The Stalling of Tapered Wings.

This subject has recently received a good deal of attention in this country and in America in view of the unpleasant characteristic of tapered wings, especially those of high taper ratios, of dropping a wing when stalled in a more vicious way than rectangular wings. It has also been observed in flight and on models in the wind tunnel that for highly tapered wings there is a very definite tendency to stall first at the tips and not at the centre. The stalling characteristics of wings of low taper ratios are still very much disputed, and some designers of aircraft using wings of relatively small taper ratio claim stalling characteristics comparable to those of rectangular wings.

When first faced with the phenomenon one is inclined to explain the behaviour at the stall of tapered wings solely on the basis of the aerofoil theory. The aerofoil theory indicates, as illustrated in Fig. 7, that an elliptical wing or a wing

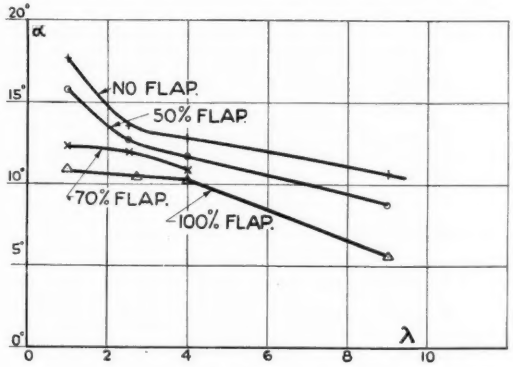


Fig. 10.

of taper ratio of about 2 : 1 which approaches the elliptical distribution should stall simultaneously over the whole span. Wings of higher taper ratio should stall first at a point somewhat inboard of the wing tips as there the local C_L or the effective angle of incidence reaches a maximum value prior to other portions of the wing. However, it has been found that the aerofoil theory alone does not give a satisfactory explanation and that a number of other parameters have to be considered. Tests carried out by Millikan (14) at the Pasadena Institute of Technology, indicated that for a wing of a given taper ratio the characteristics in stalling changed decisively as the aspect ratio of the wing was increased.

More recent tests by Irving at the N.P.L. and observations in flight by Gray (15) have indicated the existence of a spanwise flow which depends on the direction of sweepback. On a tapered wing with no sweepback of the leading edge and a sweep forward of the trailing edge, Irving observed a transverse flow near the trailing edge which was directed from the tips towards the centre of the aerofoil. A similar type of flow was observed by Gray on wings which had a negative angle of yaw. *Vice-versa* an outward flow (towards the tips) was observed on a tapered wing having a swept back leading and correspondingly in full-scale on a monoplane with positive angle of yaw. Corresponding to the direction of this secondary flow the stalling of the tips was either delayed when

the flow had an inward direction and accelerated when the flow had an outward direction. The explanation for this phenomenon, as given by Gray (*Flight*, July 16th, 1936), due to the transverse pressure gradient, is not convincing. C. N. H. Locke, of the N.P.L., has pointed out in a letter addressed to *Flight* (16) (August 27th, 1936) that in the case of a yawed aerofoil the flow may be resolved into a two-dimensional flow in planes normal to the aerofoil together with a uniform velocity along the span which will not affect the equilibrium of the transverse flow. The spanwise component of the flow will affect the boundary layer, especially when the aerofoil is stalled. In the case of a yawed aerofoil, or in the case of an aerofoil with swept forward trailing edge, dead air will be transported from the tips towards the centre thus delaying the stalling of the tips and accelerating the stalling of the tips and accelerating the stalling of the centre by comparison with the corresponding aerofoil with straight trailing edge.

This aspect of stalling still requires fuller research, and it seems a little too early to form a definite opinion, but it is most likely that the phenomenon of the spanwise dead air transport will explain certain observations in regard to the point where the breakaway of the flow first occurs on the wing which are in contradiction to the ordinary aerofoil theory.

Apart from this phenomenon it is usually overlooked when applying the general aerofoil theory that the wing section along the span is not constant on actual monoplane wings as the thickness chord ratio varies usually from the centre towards the tip, apart from the change in chord.

In predicting the point where stalling will first occur, it is necessary to make allowance for the actual stalling angle of a section at any point of the span, and by varying the geometric angle and the characteristics of the section (thickness chord ratio and camber) it should be possible to control to some extent the commencement of burbling in relation to the wing plan form.

(a) Influence of Twist.

A mere twist, *i.e.*, an outwash towards the tips seems to be a very obvious scheme to delay the stalling of the tips, but it is, in my opinion, a very inefficient way unless the twist becomes so excessively large that the drag and the lift distribution at small angles of incidence are substantially affected. J. Hueber (17) published some theoretical investigations in 1933 on twisted tapered wings. The distribution of twist along the span was so chosen as to obtain an elliptical C_L distribution. The following table contains the angle of twist and the increase of induced drag compared with the minimum value for elliptical lift distribution at an overall $C_L = 1$.

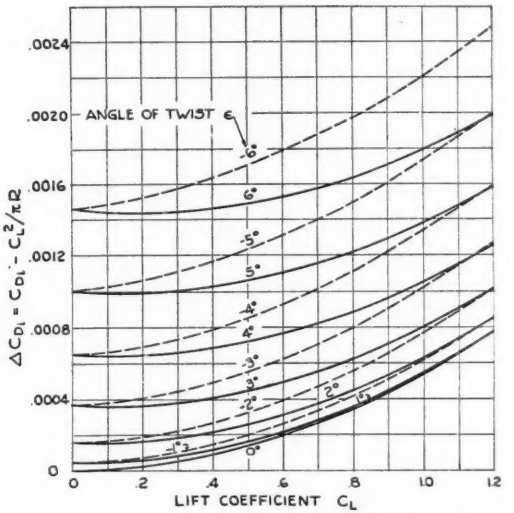
Taper Ratio.	Angle of twist equals difference of geometric angle at root and tip for overall $C_L = 1$.	Di/Di ellip.
5	20	1.21
2.5	19	1.11
1.25	15	1.01
1	13.5	1.0

On a wing which was actually used on a glider consisting of a rectangular centre portion and tapered tips (taper ratio = 1.54) the twist required for the tapered portion was $-9.5°$.

Hueber's assumption of an elliptical C_L distribution, although rational, was quite arbitrary and may appear too severe. In a more recent publication on the influence of twist by Albert E. Lombard (18) in the *Journal of the Aeronautical Sciences* (" Technical Developments of the Curtiss Wright Coupé ") the author comes to the conclusion that even a mild twist not exceeding $-6°$ is a very inefficient way of obtaining good stalling characteristics. The wing investigated by Lombard had an aspect ratio of 6.724 and a taper ratio of 2.16. The increase

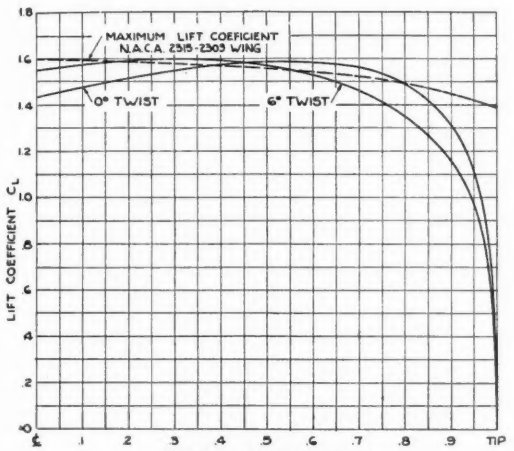
in induced drag for various angles of twist and the resulting C_L distribution are shown in Fig. 11.

For a twist up to 2° the increase in induced drag is not serious, amounting to not over 1 per cent. of the drag for an average aeroplane, but as the twist is increased above 2° the additional drag becomes appreciable.



ΔC_{Di} FOR TAPERED WING.

ASPECT RATIO = 6.724 $dC_L/d\alpha_0 = 5.84$/rad.
TIP CHORD = .461 ROOT CHORD.



LIFT COEFFICIENT ALONG TAPERED WING.

$C_{L\,AV.} = 1.50$
ASPECT RATIO = 6.724 TIP CHORD = .461 ROOT CHORD.

FIG. 11.

(b) Twist Combined with Change of Camber.

More efficient than a mere twist is the combination of twist and change of camber as follows from Fig. 12, where lift curves are plotted for a section of small and a section of higher camber. Provided that the difference in α_{max} is smaller than the difference in zero lift angle, it is obvious that the total angular range for the more highly cambered section is greater than for the section with low camber. This increase of total effective angular range can be utilised to delay stalling of the tips. If we consider first a section of a relatively low camber near the root of the aerofoil, and if we base our consideration on a given theoretical C_L distribution depending on the taper ratio of the wing, a certain local value of C_L is required. The margin against stalling of this section

$$\gamma = (\alpha_{max}) \text{ absolute} - \alpha_1 = C_{Lmax}/(dC_L/d\alpha) - C_L/(dC_L/d\alpha)$$

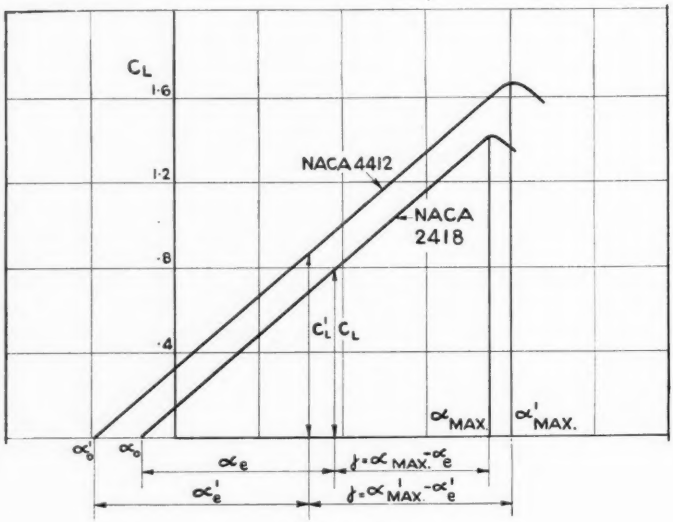


FIG. 12.

$dC_L/d\alpha = 2\pi$ (theoretical value), but this value is actually slightly influenced by thickness chord ratio and camber; (α_{max}) absolute $= \alpha_0 + \alpha_{max}$ where α_0 = zero lift angle and α_{max} is the angle at which C_{Lmax} is measured from $\alpha = 0$.

Let us now consider a section further outboard at which the local lift coefficient required may be C_L'. The local margin against stalling at this portion of the wing is therefore:—

$$\gamma' = (\alpha'_{max})/\text{absolute} - C_L'/(dC_L/d\alpha).$$

It is obvious that if $\gamma' > \gamma$, the wing will stall first at the inner section and the difference between γ' and γ will then represent the margin against stalling of the outboard section compared with the inboard one. It can easily be verified that the required geometric angle and therefore the necessary amount of twist to produce the value of C_L' is equal to the difference of the respective zero lift angles of the two wing sections.

An investigation on these lines has been made for wings of various taper ratios, and the assumptions in regard to distribution of thickness chord ratio

and camber ratio along the span are plotted in Fig. 12*a*. This figure also contains the amount of twist required in order to produce the theoretical C_L distribution for a given overall C_L value. It seems advisable to choose an overall C_L value corresponding to climbing flight. For this condition of flight there will then be no increase of induced drag compared with an untwisted wing of constant section. Fig. 13 shows the distribution of the margin against stalling across the span for wings of various taper ratios and for wing sections having the maximum camber at various positions of the chord. The characteristics are taken from N.A.C.A. Report No. 460 (1), As the figure indicates sections with the camber at 0.4 and 0.5 of the chord give satisfactory results while sections with the camber at 0.3*c* are less suitable.

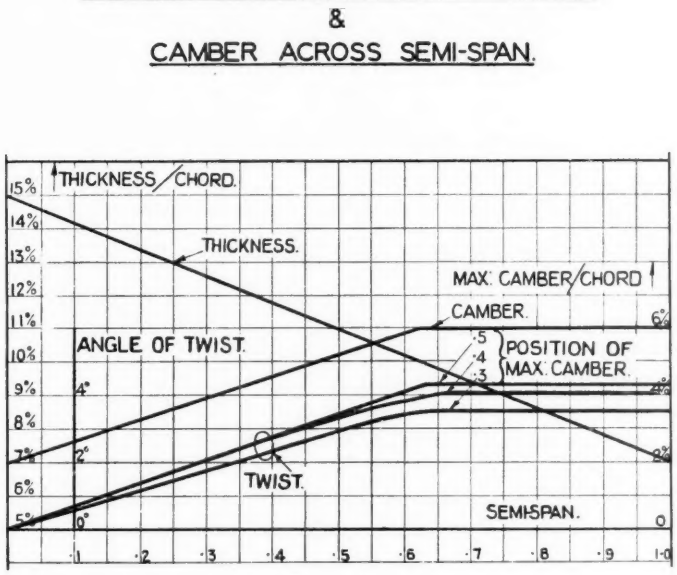


FIG. 12*a*.

(c) *Tapered Wings and Wing Tip Slots.*

The method described above is based upon the increase of angular range mainly due to the lower zero lift angle of higher cambered sections compared with those of low camber. The obvious disadvantage, of course, is the difficulty to fair in sections of varying camber and also the concentration of high torque at the tips where the resistance of the wing against torsional deflection is weakest. Another method consists in utilising such sections where the angular range is increased at the high lift end of the angular range, for example, by using a slotted section at the tips.

Sucking away the boundary layer is also a means to increase the high lift end of the angular range, and one could conceive a method to prevent tip stalling on this basis. Such a method would, however, suffer from the obvious practical disadvantage that the effect is bound up with the working of the power plant which drives the pump.

5. Tapered Wings and Longitudinal Stability.

(*a*) *Analysis of Pitching Moments.*

Most designers who began to design monoplanes with tapered wings and applied the knowledge and experience gained from biplane design have been faced with the difficulty to obtain satisfactory longitudinal stability and often

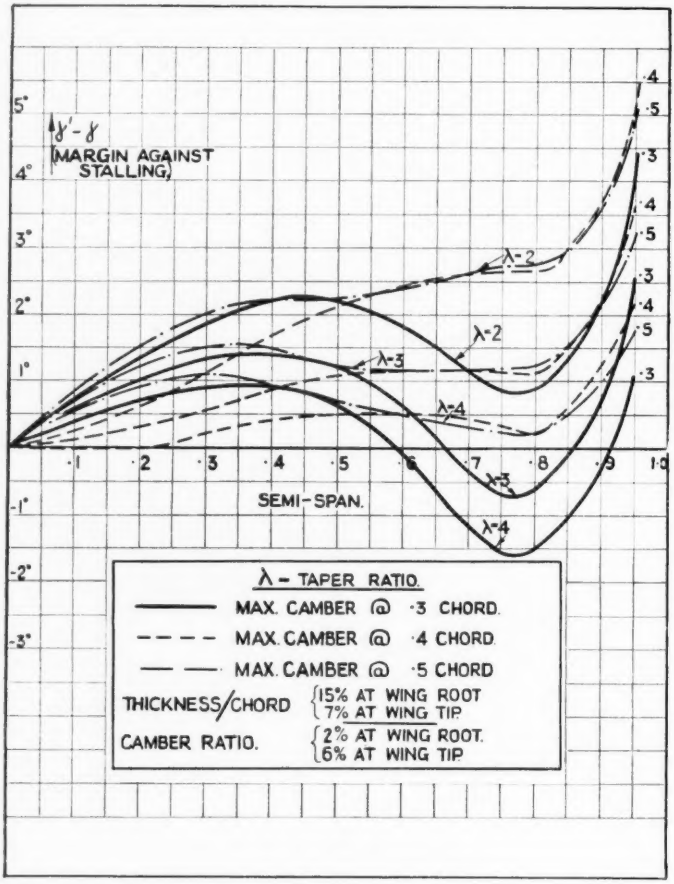


Fig. 13.

found it necessary either to shift the C.G. much more forward of the originally assumed position or to increase the tail volume considerably beyond the values which gave satisfactory stability on biplanes. There are various reasons which account for this mysterious instability of the monoplane, and in the following I propose to deal with some of the major causes, but I am not claiming that the effects mentioned are the only ones. The conclusions drawn are based on a careful analysis of wind tunnel tests with a twin-engined monoplane having a taper ratio of about 4 : 1 and a tail volume of 0.55.

Fig. 14 shows a typical pitching moment diagram for a twin-engined monoplane. The resulting pitching moment has been resolved into moments for the

aircraft less tail and for moments produced by the tail only. A further analysis of the pitching moments of the aircraft less tail is contained in Fig. 14*a*. One of the most striking facts revealed by this analysis is the large influence of the engine nacelles and the body on the total moment. At an angle of incidence of 6° the combined unstable pitching moment due to nacelles and body

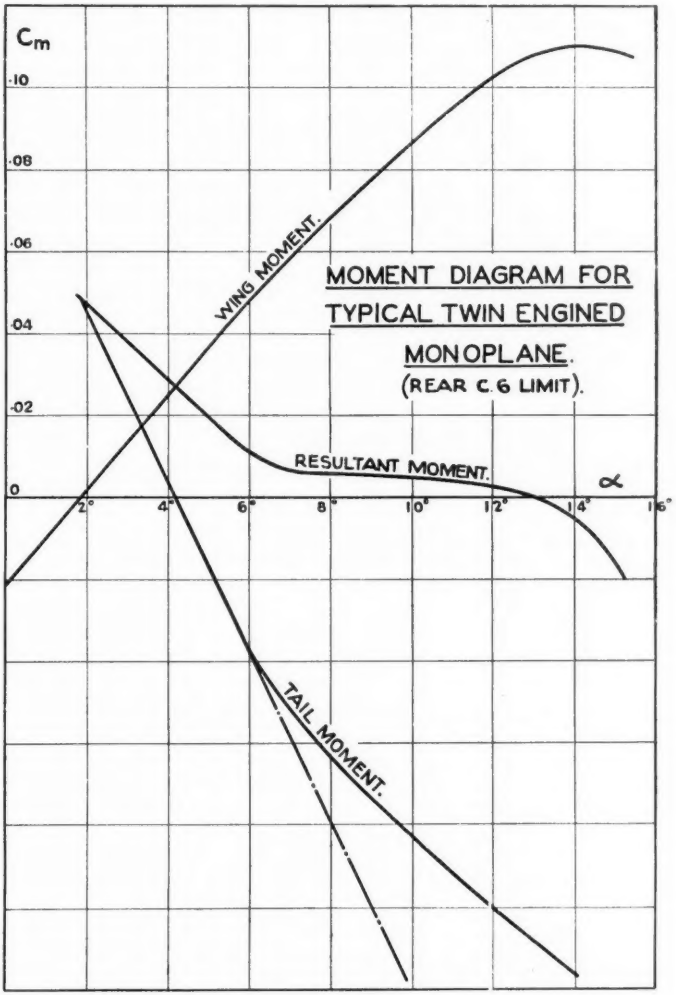


FIG. 14.

is about twice as large as the wing moment alone. I feel sure that in many cases where the design was not from the beginning based on wind tunnel tests, this effect of nacelles and body has been greatly under-estimated. The effect of the slipstream on the overall pitching moment less tail is relatively small.

The curve representing the pitching moment due to the tail reveals that from an angle of 6° onwards the tail efficiency is considerably reduced; obviously, too,

the fact that the tail is in the wake of reduced pressure which is shed by the centre portion of the wing.

(*b*) *The Effect of Downwash.*

Apart from screening off the tail, tapered wings reduce the stabilising effect of the tail surface by a concentration of downwash behind the centre portion of the wing. There are no systematic measurements of downwash angle as a function of taper ratio available, but by calculating the downwash at the locus of the tail either by means of Helmbold's (19) or Glauert's formulæ a fairly good agreement has been found to exist between the calculated value and actually measured values. Even if the absolute values are not quite in agreement there

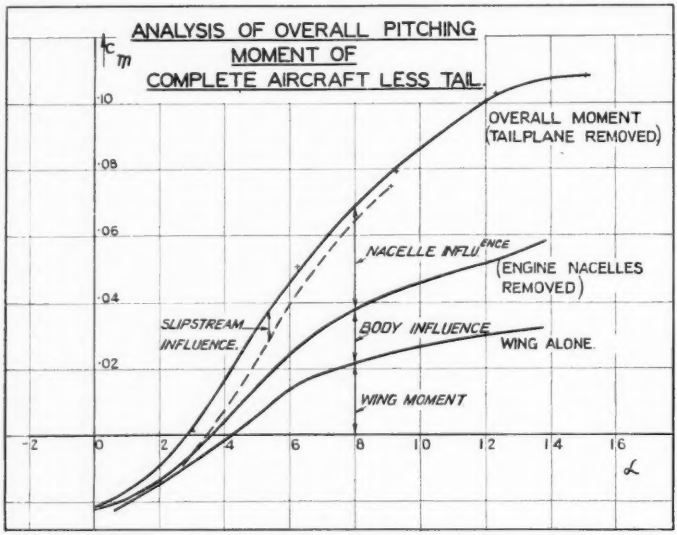


FIG. 14*a*.

is very little doubt that a tendency of the central downwash to increase proportionally to the taper ratio definitely exists. In Fig. 15 calculated downwash angles at the locus of the tailplane are plotted over taper ratio at a lift coefficient $C_L = 1$. By a simple consideration, suggested by my collaborator Mr. Stafford, one can now determine the rear C.G. limit at which indifference occurs, *i.e.*, where

$$dC_{Mw}/dC_L = dC_{MT}/dC_L.$$

Considering that the wing moment about the C.G. is

$$C_{Mw} = C_{Mo} + C_L\,(x - 0.25)\,c_{mean}$$

where C_{Mo} = zero lift moment.

xc_{mean} = distance of C.G. from leading edge of aerodynamic mean chord.

c_{mean} = aerodynamic mean chord,

and the tail moment

$$C_{MT} = -F\,(\partial C_{Lt}/\partial\alpha)\,(\partial\alpha/\partial C_L)\,(S_t l/S_w c)\,(1 - \partial\beta/\partial\alpha)$$

where F = tail efficiency (takes into account screening effect).

C_{LT} = lift coefficient acting on tail surface.

S_T = tail surface.

l = distance of C.P. tail surface from C.G.

S_w = wing surface.

$\partial\beta/\partial\alpha$ = change of downwash angle β with angle of incidence α.

For a typical case the value of the constant

$$F\,(\partial C_{LT}/\partial\alpha)\,(\partial\alpha/\partial C_L)\,(S_t l/S_w c)$$

has been found to be 0.261. With this value and the calculated values for $\partial\beta/\partial\alpha$ the rear limit of the C.G. x = fraction of chord has been determined where neutral stability occurs. The results of this calculation are contained in the following table:—

C_o/C_t	$\partial\beta/\partial C_L$	$\partial\beta/\partial\alpha$	$1-\partial\beta/\partial\alpha$	X
0	30.4	0.63	0.37	0.276
4	24.2	0.50	0.50	0.300
2	20.8	0.43	0.57	0.318
1.33	18.5	0.383	0.617	0.330
1.0	16.70	0.345	0.655	0.341

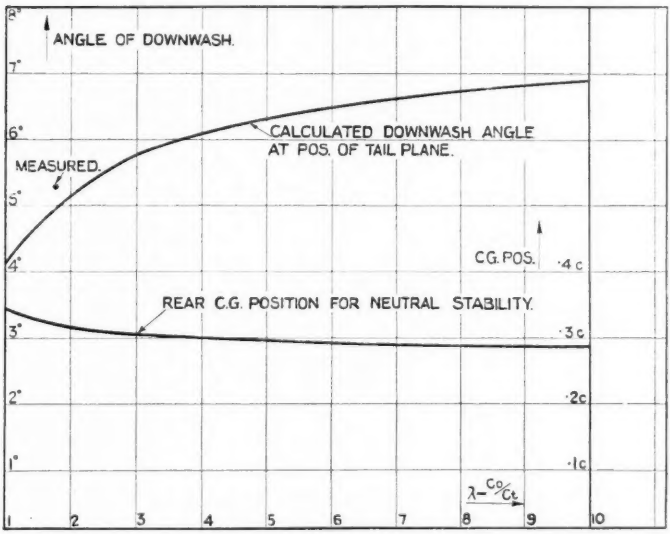


FIG. 15.

In Fig. 15 a curve has been plotted indicating the rear C.G. position for neutral stability. It becomes evident that whilst for a rectangular wing the rear C.G. limit under the given assumptions would be c.341, this limit is reduced to 0.3 for a wing of taper ratio 4.

(c) Influence of Wing Fillets.

Wing fillets have been found to exert a strong de-stabilising influence on the overall pitching moment as is indicated in Fig. 16 from a paper by Mr. Hibbard (20), Chief Engineer of the Lockheed Company, which was delivered in Germany in October, 1935. The curves refer to the Lockheed "Electra."

The fillet has been ultimately deleted on this aircraft, which not only resulted in better stability but also in a slight improvement of the performance.

Obviously it is possible to prevent expansion at the juncture of fuselage and wing by careful design, and fillets which were once very much in vogue are gradually going out of fashion again.

Summarising, I am therefore inclined to trace back the greater instability which has been observed on monoplanes with tapered wings to the following causes:—

1. Large unstable pitching moments due to engine nacelles and body.
2. A more pronounced wake effect due to the greater thickness of the root section resulting in screening off the tail and reducing the tail efficiency.
3. Increase of downwash due to the concentration of lift at the centre of the wing and also due to slipstream.
4. De-stabilising influence of wing fillets.

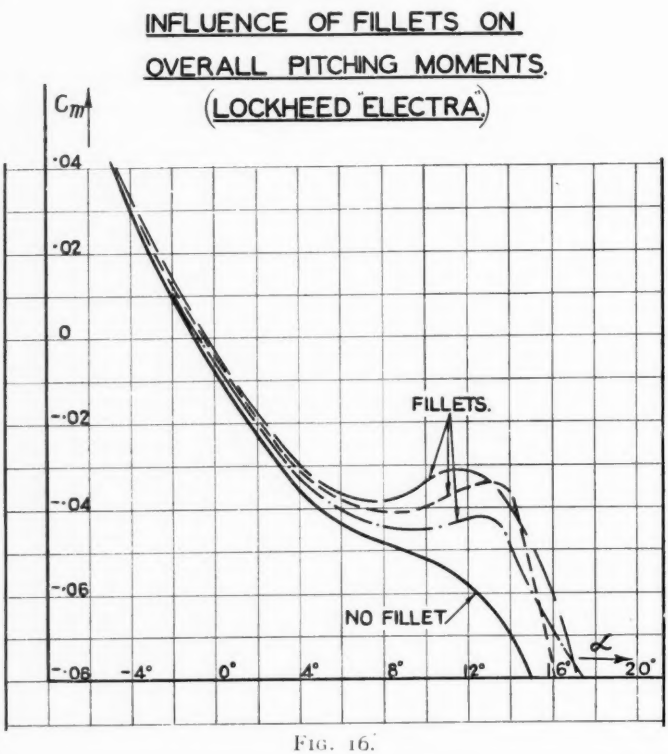


FIG. 16.

There are, of course, some other possible causes; greater instability may result from the use of trimming tabs and from mass balancing the elevators, but they do not come within the scope of this paper.

(d) Change of Trim due to Flap Setting.

Apart from actual stability problems, difficulties were encountered by some designers due to the change of trim when the flaps were lowered. In some cases the effect was less noticeable and even of different sign than in others. The differences could be traced back either to a smaller change in pitching moment or to a larger tail volume. It is obvious now that one can design any aircraft fitted with flaps on the basic assumption that no change of trim should be experienced when the flaps are lowered at a certain value of C_L, for example, for a C_L corresponding to a speed 20 per cent. above stalling speed. The tail volume

has to be chosen in such a way that, taking into account the increase of effective angle due to the increased downwash with flaps down, the increase of stable pitching moment due to tail equalises the increase of unstable pitching moment of the wings due to the flap setting. This condition then really becomes the decisive criterion determining the amount of tail volume required which in most cases over-rides the requirements of stability. Generally speaking, split flaps have been found to give a slightly smaller change in pitching moment than slotted flaps.

For a typical low wing monoplane ($\lambda = 1.85$) fitted with a partial flap (overall flap span = 0.665 of wing span) the change in moment due to setting the split flap (15 per cent. of chord) at angle of 60° was $\Delta C_M : 0.134$ compared with $\Delta C_M : 0.182$ for a slotted flap (20 per cent. of wing chord) at the same flap angle. In both cases the overall C_L of the wing was $C_L = 0.8$ (21).

It is evident that the change of pitching moment is increased for higher taper ratios. This effect will be partly offset again by the probably stronger downwash for wings of higher taper ratio, and a more general experimental investigation measuring both influences would be very helpful from the designers' point of view.

6. Tapered Wings with High Lift Devices.

(1) *General Discussion of Existing Devices.*

The development of clean fast monoplanes fitted with highly loaded wings has forced upon the designer the use of special devices which increase the drag and the lift when landing. Up to now many designers have placed relatively greater importance on the increase of drag, but it is clear that with wing loadings approaching values of 30 and 40lbs. per sq. ft. greater attention has to be given to the lift increasing properties of the wing as is necessary when the wing loadings are round about 20lbs. per sq. ft. The use of lift increasing devices has made it possible to reduce the size of the area of the wings, and the possibility of steepening the gliding angle by increasing the drag combined with more efficient use of wheel brakes, have made it possible to land at higher landing speeds than those which were considered reasonable for biplanes. A higher brake torque can usually be applied on monoplanes as compared with biplanes due to the closer proximity of the C.G. from the ground. Although the composite wings now used on monoplanes are considerably heavier per sq. ft. than biplane wings used to be, the percentage structure weight of the wings on modern monoplanes is not higher and in some cases even lower than the equivalent figures for biplane constructions. The application of flaps and other devices to the monoplane wing has therefore helped to deflect the old argument which was once so strongly maintained by the convinced adherents of biplane construction, namely, that the monoplane was inherently heavier than the biplane. I should like to explain this point by the following numerical consideration.

If W_w = wing weight and w = wing weight per sq. ft., the weight of two wings of difference characteristics will vary as :—

$$W_{w1}/W_{w2} = (w_1/w_2)\,(C_{L\,max\,2}/C_{L\,max\,1})\,\{\,(v_{min\,2}/v_{min\,1})\,\}^2.$$

Average figures for a biplane are $w = 1.7$, $C_{Lmax} = 1.2$, $V_{min} = 50$ m.p.h. For monoplanes $w = 3.2$, $C_{Lmax} = 1.9$, $V_{min} = 60$ m.p.h.

Hence

$$W_w \text{ monoplane}/W_w \text{ biplane} = 0.83.$$

The composite wings now in use on modern monoplanes utilise the following devices :—

Split flaps.
Slotted flaps, including the double wing variation as used in the Junkers designs.
Fowler flaps.

Tip slots combined with partial flaps.
Partial flaps combined with drooping ailerons.
Complete lift slots combined with flaps.

A brief analysis of these devices leads to the following general conclusions.

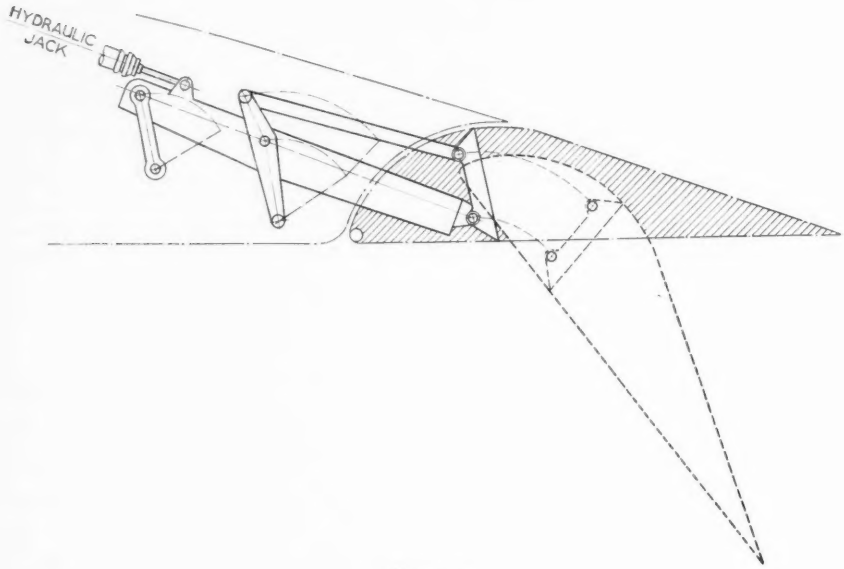


FIG. 17.

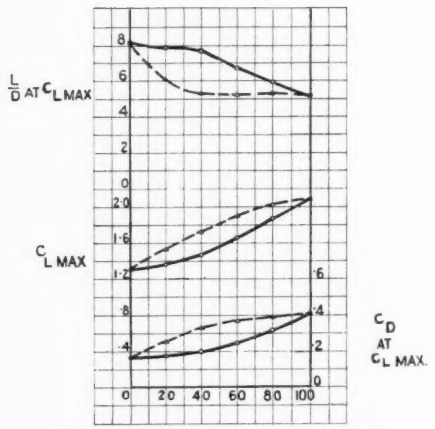


FIG. 18.

The slotted flap (Fig. 17) offers the best all-round solution as it gives high values of $C_{L\max}$ and drag (at 60° flap angle) for landing, and for take-off an increase in lift without undue drag increase with, say, $20 \div 30°$ flap angle. The hinge moments are low and, therefore, the control mechanism light and simple.

The Fowler wing gives an apparent higher value of $C_{L\max}$ due to the virtual increase in wing area with the flap extended, but is complicated mechanically. The double wing flap has the disadvantage of the added drag of the supporting brackets.

The split flap gives a good increase in $C_{L\max}$ and drag for landing, but owing to the high drag even at smaller angles cannot be used to aid take-off except on machines of high power/wt. ratio. The hinge moments are very high and the control is therefore heavy.

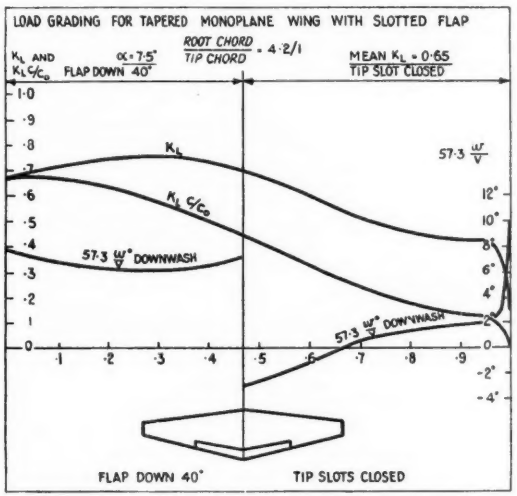


FIG. 19.

(b) Partial Flaps.

So far only partial flaps are the rule on existing aircraft. The partial flap gives, of course, a smaller $C_{L\max}$ than the full span flap as indicated in Fig. 18, which is taken from N.A.C.A. Technical Note No. 505 (22). This report refers to tests on a tapered wing of taper ratio 5.

There are two main reasons why full span flaps have not been successful. The first is that when full span flaps are used the conventional aileron has to be replaced by a new type of lateral control. So-called " park bench " ailerons have once been suggested and tried out, but have been abandoned again. A different attempt was made by Messerschmitt, who replaced the ailerons by a spoiler. Although the control was efficient in regard to rolling moments produced, this method was again abandoned because of the lag in control at smaller spoiler movements. On the Fieseler Fi. 97 ailerons which only gave an upward movement were used. Springs had to be introduced in order to prevent the ailerons from being sucked up by the flow, resulting in a very heavy aileron control at normal angles. Another important reason which operates against the use of constant span flaps is their influence on damping in roll when approaching the stall.

Some fundamental tests by Irving, already referred to above, have clearly shown that full span flaps not only cause a higher degree of instability at the

stall, but also make the loss of damping in roll occur earlier than on a normal wing or on a wing fitted with partial flaps only.

(c) Partial Flaps with Tip Slots.

Fig. 19 shows a calculated distribution of load grading, lift coefficient and downwash for a tapered wing of taper ratio 4.2 fitted with a partial flap set at 40°. The most interesting fact expressed by this diagram is the concentration of downwash towards the centre of the wing and the corresponding reduction of downwash at the tips. There is actually a certain amount of upwash at the point where the flap ends and the ordinary wing begins. The reduction in downwash at the tips results, of course, in an increase of the effective angle which is the difference between the geometric angle and downwash angle v/V. This distribution of downwash explains, in my opinion, the precipitated loss of damping in roll as observed by Irving.

When we first, in the course of theoretical investigations of the aerodynamic characteristics of tapered wings, came across this phenomenon, the suggestion occurred at once that fitting a tip slot to a tapered wing fitted with a partial flap

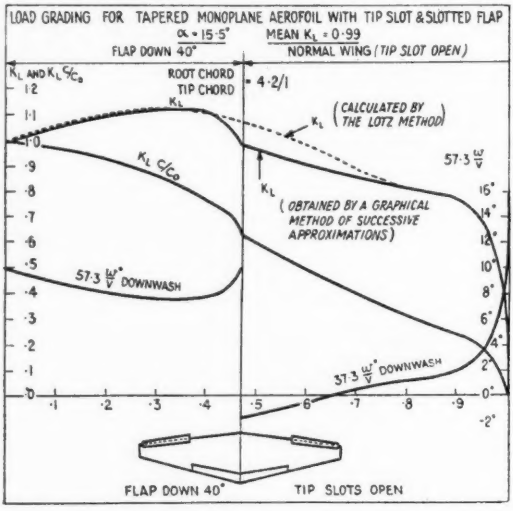

LOAD GRADING FOR TAPERED MONOPLANE AEROFOIL WITH TIP SLOT & SLOTTED FLAP
α = 15·5°
MEAN K_L = 0·99
FLAP DOWN 40°
NORMAL WING (TIP SLOT OPEN)
K_L AND $K_L C/C_0$
ROOT CHORD / TIP CHORD = 4·2/1
K_L
(CALCULATED BY THE LOTZ METHOD)
$K_L C/C_0$
57·3 w/V
(OBTAINED BY A GRAPHICAL METHOD OF SUCCESSIVE APPROXIMATIONS)
57·3 w/V DOWNWASH
FLAP DOWN 40°
TIP SLOTS OPEN

FIG. 20.

should not only prove to be a suitable means to delay the stalling of the tip, but also a source of additional lift obtainable at a relatively small geometric angle of the wing. Fig. 20 shows a calculated lift distribution for a tapered wing with partial flap and tip slots. The mean C_L of about 2 is obtained due to a very full effective C_L distribution across the span. It is obvious that the slot contributes materially to the $C_{L\max}$ obtained either directly and by allowing the flaps to reach their full lift.

One of the main arguments brought forward against the slot as a lifting device has always been the large geometric angle necessary to utilise the maximum lift. This characteristic, on the other hand, makes the wing tip slot particularly suitable for a tapered wing fitted with a partial flap because of the big increase of effective angle at the tips, and in view of this it is possible to obtain a very large percentage of the available maximum lift of a tip slot at a relatively small geometric angle of the whole aerofoil. The functions of a tip slot on a rectangular wing are practically limited to the maintenance of damping in roll

at the stall. A contribution to the total lift is not possible as the super-stall angle at which the tip slot reached its maximum lift is far beyond the stalling angle of the ordinary aerofoil. In fact, the super-stall angle of a rectangular wing with tip slots is considerably larger than the stalling angle of a full span slot. In my paper on "Control Beyond the Stall," read before the Society in 1931 (23), I explained that this was due to the concentration of the downwash at the tips of a rectangular wing. In the case of a highly tapered wing the super-stall angle of the slots is not so far removed from the stalling angle of the main wing because of the downwash concentration at the centre. Corre-

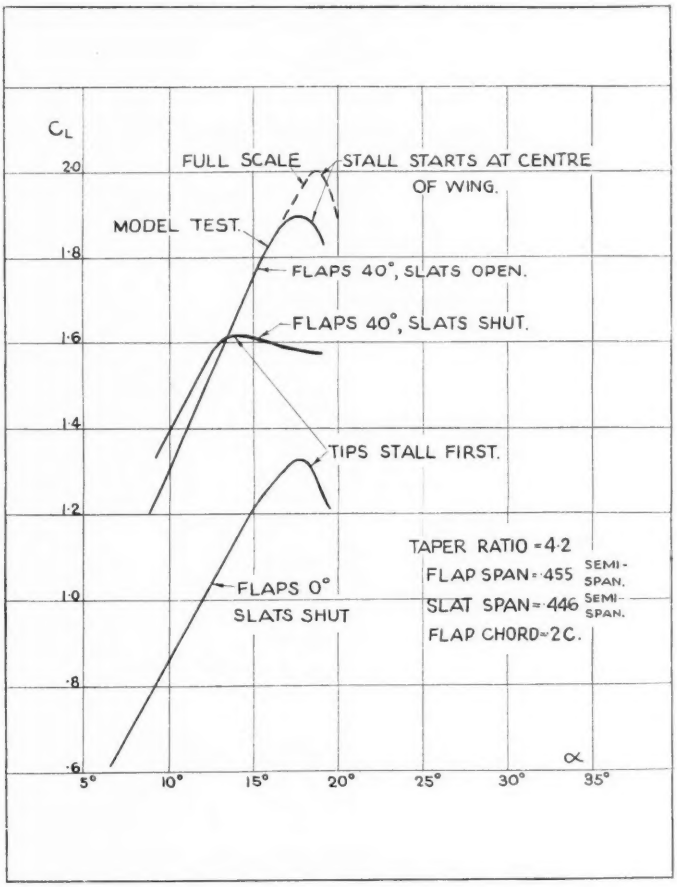


FIG. 21.

spondingly the tip slot of a tapered wing contributes materially to the maximum lift. Although the margin in regard to loss of lateral stability is less for a tapered wing fitted with tip slots than for a rectangular wing the stabilising effect has been found quite sufficient in practice. The theoretically predicted C_L values for tapered wings fitted with partial slots and tip slots have been well confirmed by a number of wind tunnel tests and by measurements in flight. These tests also indicate that the geometric angle at which the additional lift

of the tip slots can be utilised is reduced as the taper ratio and the aspect ratio increase, while for low taper ratios the angle at which the maximum C_L of the wing tip slots occurs approaches values similar to those on rectangular wings. Highly tapered wings of fairly high aspect ratio are therefore essential to derive the maximum benefit from the lifting contribution of a tip slot. The tip slot of such a wing can be considered in its effect as an extension of the partial flap without the disadvantage of introducing a new type of lateral control and without losing damping in roll at the stall. The influence of taper ratio on the angle at

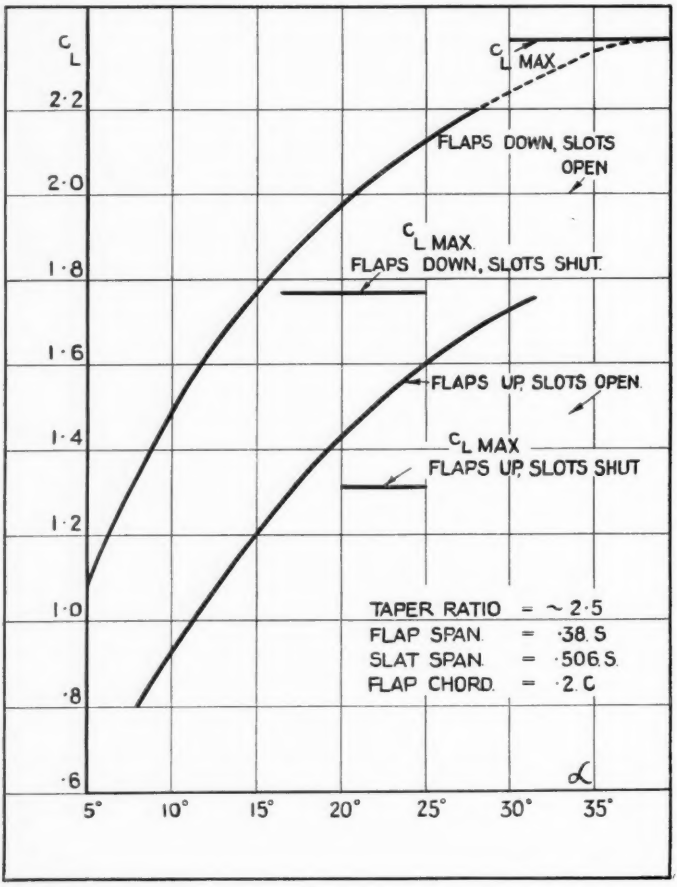


FIG. 22.

which the maximum lift of the tip slots can be obtained has been confirmed by a series of wind tunnel tests on tapered wings of various taper ratios fitted with partial flaps and tip slots. Some results are contained in Figs. 21 and 22. Fig. 21 contains lift curves for a wing of taper ratio $\lambda = 4.2$ fitted with partial flaps of 0.455 semi-span and wing tip slots of 0.446 semi-span. The tip slots increase the maximum lift obtained with flaps only from 1.6 to 2.0 and the maximum lift of this combination of flap and tip slots occurs at practically the same angle where the normal aerofoil reaches its maximum lift.

Fig. 22 refers to flight tests on the Hendy " Heck " (24). The taper ratio is 2.5. The maximum lift of the wing with flaps and tip slots in operation occurred at an angle of 36° which, of course, makes it impossible to utilise the very substantial lift increase due to the tip slots. However, their stabilising effect permitted the safe use of the lift increase due to the flaps, which was not possible when the tip slots were shut.

(d) Partial Flaps Combined with Drooping Ailerons.

Another method of approaching the maximum C_L obtainable with a continuous flap without ensuing the disadvantages mentioned, consists in drooping the ailerons on a wing fitted with a partial flap. The angle at which the ailerons are to be drooped while still workable as ailerons has to be, of course, less than the angle of the flap setting. This method has been tried out in this country on an Airspeed " Courier " and in Canada on the Norduyn " Norseman." Wind tunnel results on this method are not available, but full scale evidence has been extremely satisfactory on both machines. On the Airspeed " Courier " the following results have been obtained in the course of official tests at Farnborough.

Flap Setting.	C_L max.
1. All flaps neutral	1.44
2. Flaps down, ailerons neutral	2.05
3. Flaps down and ailerons down	2.44

Lateral control and stability on both machines was quite satisfactory, which may be due to the use of slotted ailerons on both machines of a type where the upgoing aileron closes the slot. Thus a kind of mild interceptor effect is obtained.

(e) Combined Complete Slots with Flaps.

A very high maximum C_L can be obtained by this method which, however, is only suitable for wings of fairly low taper ratio as on wings of higher taper ratio, for the same reason as explained above for wing tip slots, the inner slots were found to be less efficient than the outer ones. In other words, it was not possible to obtain the maximum lift increase due to the inner slots simultaneously with the outer tip slots.

A very good example of this method is the original " Taifun " designed by W. Messerschmitt and built by the B.F.W. of Augsburg. This machine took part in the last round Europe flight. On a commercial version of this type the inner slots have been deleted

(f) Summary and Future Outlook.

Reviewing available wind tunnel and full scale results, it is, of course, difficult to form a correct comparison on an equal basis in view of great differences in Reynolds number, but the values of maximum C_L available on tapered wings with the above described technical devices may be summarised in a rough and ready way for 20 per cent. chord flaps as follows:—

Partial flap (slotted or split) (50 per cent. of semi-span), C_{Lmax} about 1.8 to 1.9.

Partial flap plus tip slot (slotted or split) (50 per cent. of semi-span, 20 per cent. chord), C_{Lmax} 2.1 to 2.2.

Partial flap (Fowler wing), C_{Lmax} about 2.3/2.4 (25).

Partial flap (slotted or split type) combined with drooping ailerons, $C_{Lmax} = 2.4$.

Partial flap (slotted or split type) combined with drooping ailerons, plus tip slots, $C_{Lmax} = 2.65$.

Complete lift slots plus partial flaps (slotted or split), $C_{Lmax} = 2.5/2.8$.

The Fowler wing has recently been tried out in full scale in America by the Martin and the Douglas Companies, and previously in Germany by the Fieseler

Company on the Fi.97. Difficulties were experienced in finding a light and simple mechanism for the operation. These difficulties can be appreciated if one realises that the lift coefficient on the Fowler flap alone is of the order of 3, and that accordingly a very large proportion of the total lift has to be shifted over a distance of one-quarter of the chord whilst the available height of the wing section decreases rapidly towards the trailing edge. Besides, I understand that in America difficulties have been experienced in utilising the full lift available in a normal landing or during the take-off, due to the deflection of the strong downwash from the ground which made it impossible to maintain the angle required to obtain the maximum lift.

It would appear that this difficulty will be experienced on our present type of aircraft when any ultra high lift device is being applied and will force us to adopt a different technique of landing, of the " pancake " or " crash " type, instead of the customary floating out.

If we assume average figures for present-day aircraft of wing loadings averaging 20 lbs./sq. ft. and maximum lift coefficients of about 1.8 to 1.9, lift coefficients of the order of 3.6 to 3.8 are required to maintain the same landing speed at 40 lbs./sq. ft. wing loading. The above estimate of the $C_{L\max}$ obtainable with known means indicates that such high values of $C_{L\max}$ are scarcely obtainable even by the most efficient combination of the existing devices. If on future aircraft the wing loading is to be twice as high as our present standard, we have either to admit a higher landing speed or we have to look forward to new means to increase the maximum lift. The only known means to provide such a high lift coefficient consists in sucking away the boundary layer. Wind tunnel tests carried out at Langley Field have indicated that values for maximum C_L of about 3.5 can be obtained at a relatively small expense of the available h.p. Adherents of boundary layer control point out that with the introduction of decentralised power plants and variable pitch propellers which can be feathered, it is possible to utilise one element of the power plant for driving the pump which removes the boundary layer. Inherent in this method, however, is the disadvantage of the large angle of incidence at which maximum C_L is obtainable. Very large landing angles are therefore necessary to utilise these high lift coefficients, and radical changes in the general design of the aircraft are required in order to justify the application of this method.

III.

Typical Structural Solutions for Cantilever Wings.

1. Limitation of Subject.

The structure of a wing consists of the following components:—

(*a*) Spar flanges or stressed skin to deal with the longitudinal loads due to bending.
(*b*) Shear webs to deal with the total shear.
(*c*) A torsion member which deals with the torque of the wing, and
(*d*) Secondary structure.

The torsion member can either take the form of a thin-walled box or a D-shaped nose, or it can consist of a special torque bracing (Stieger monospar wing or Wallis geodetic construction).

In the following I shall deal only with all-metal structures where the torsion member consists of a skin-covered structure. I shall also exclude wooden structures from a closer consideration, partly because of my limited personal experience and partly because of the definite trend towards all-metal construction, especially as far as military and larger aircraft are concerned.

There is no doubt, however, that the cheapness and the attractive simplicity offered by wood as a material (especially for the stressed-skin type of structure)

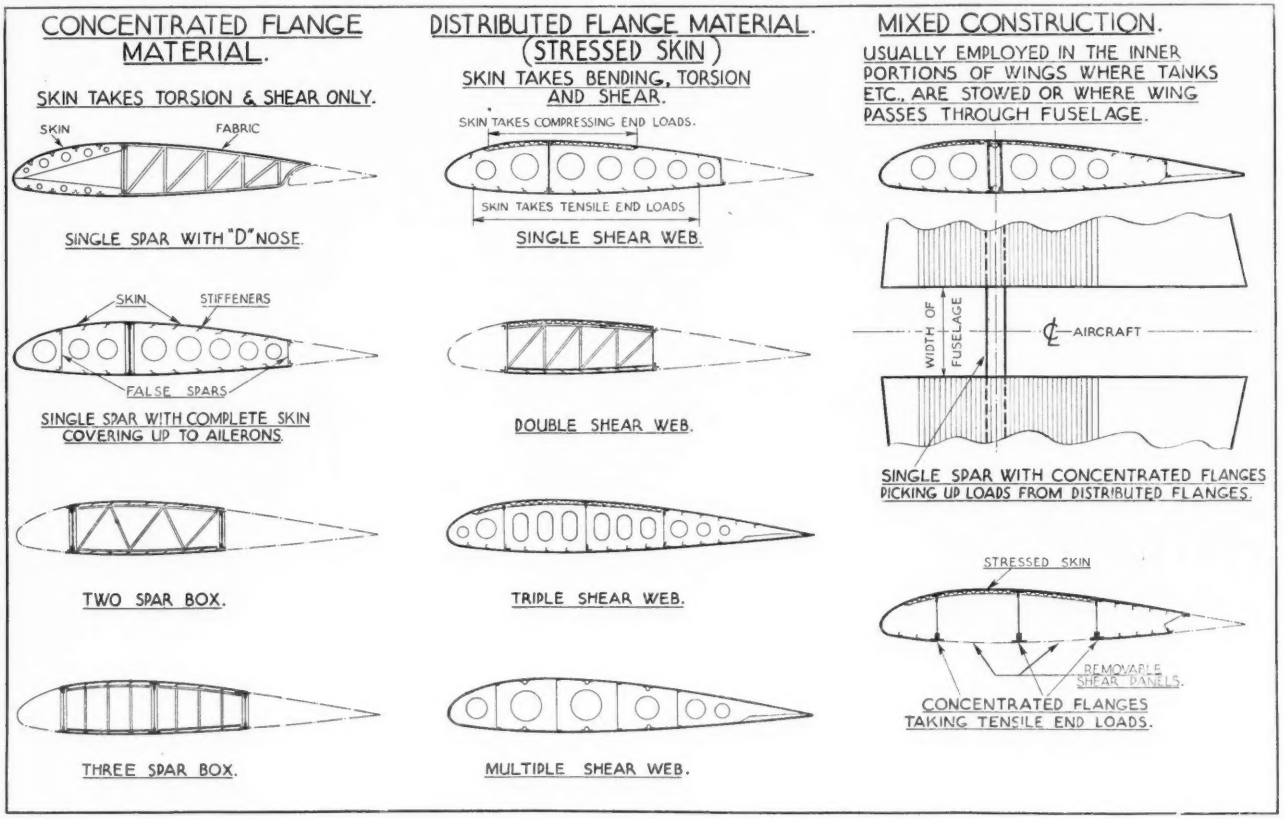

CONCENTRATED FLANGE MATERIAL.
SKIN TAKES TORSION & SHEAR ONLY.
SKIN
FABRIC
SINGLE SPAR WITH "D" NOSE.
SKIN
STIFFENERS
FALSE SPARS
SINGLE SPAR WITH COMPLETE SKIN COVERING UP TO AILERONS.
TWO SPAR BOX.
THREE SPAR BOX.
DISTRIBUTED FLANGE MATERIAL.
(STRESSED SKIN)
SKIN TAKES BENDING, TORSION AND SHEAR.
SKIN TAKES COMPRESSING END LOADS.
SKIN TAKES TENSILE END LOADS.
SINGLE SHEAR WEB.
DOUBLE SHEAR WEB.
TRIPLE SHEAR WEB.
MULTIPLE SHEAR WEB.
MIXED CONSTRUCTION.
USUALLY EMPLOYED IN THE INNER PORTIONS OF WINGS WHERE TANKS ETC., ARE STOWED OR WHERE WING PASSES THROUGH FUSELAGE.
WIDTH OF FUSELAGE
℄ AIRCRAFT
SINGLE SPAR WITH CONCENTRATED FLANGES PICKING UP LOADS FROM DISTRIBUTED FLANGES.
STRESSED SKIN
REMOVABLE SHEAR PANELS.
CONCENTRATED FLANGES TAKING TENSILE END LOADS.

FIG. 23.

wooden wing construction will still hold its own for some time to come, especially in the field of light aircraft for private and commercial use.

In analysing skin-covered metal wing structures a second subdivision can be introduced, namely, according to the method by which the flange material is arranged, either in the form of concentrated flanges or as distributed flanges (stressed skin).

Fig. 23 shows a summary of typical forms of wing construction. Designers in this country, probably due to their greater familiarity with the methods of biplane wing construction, have with few exceptions favoured wing structures with concentrated flanges.

In the United States (especially in California), where the art of metal monoplane wing construction is a little older, designers have adopted the new technique more resolutely and have gone for the fully-stressed skin type. A mixed type of construction is usually found on inner wings, either when the inner wing has to pass through the fuselage (for example on the Lockheed Electra) or where tanks are housed in the centre portion and where thus large openings are required on the bottom surface. The removable panels used to cover up those openings are then stressed for shear only, and extruded flanges take the tensile load while the unbroken stressed skin continues to take the end loads in compression. Examples for this mixed type of construction are found in the third column of Fig. 23.

2. General Comparison in Regard to Weight of Wing Structures with Concentrated and Distributed Flanges.

The expression " stressed skin construction " is often not correctly used. It should strictly apply only to such wing structures where the material of the skin not only deals with the shear due to torsion and anti-drag but also takes to practically 100 per cent. the end loads due to bending. It is obvious that if equal stresses can be obtained in concentrated flanges and in stressed skin, the latter must score heavily over the first as no additional material is required for the torsion member. Actually, however, the design stresses in flanges of extruded material are considerably higher than those obtainable with the usual combinations of skin and stringers, and the question which type of construction is superior from the weight point of view depends on the efficiency of the stressed skin construction, *i.e.*, in the first place on the design compression stress which is obtainable.

The following is an attempt to form a fairly general comparison between the two different types of construction and to give some idea under what conditions one type of structure is superior over the other from the weight point of view.

The design problem may be formulated as follows: A box beam (Fig. 24), consisting of two shear webs and slightly curved top and bottom surfaces, is to be designed with the minimum expenditure of material. The beam has to sustain a certain bending moment and a certain torque. The shear due to bending is to be taken by the vertical shear webs, and the shear due to torque by the shell formed by top and bottom skin and the shear webs. The end loads due to bending are to be absorbed either by concentrated corner flanges (extruded sections) or by distributed stringers combined with the covering skin.

These assumptions are obviously not quite correct because the bottom skin will help to absorb tensile loads and the skin has to deal with additional shear loads. However, for this comparison these finer points are neglected in the first place.

The following notation is being used:—

$2a$ = total area of concentrated top flanges.
$2b$ = total area of concentrated bottom flanges.
f = area of skin plus stiffeners = $c \cdot t \cdot k$.
t = thickness of skin.
h = distance between spar flanges.

c = chord of box beam.
BM = bending moment.
T = torque.
f_c = design compression stress in concentrated flanges.
f_t = design tensile stress in concentrated flanges.

$$\alpha = f_c/f_t.$$

f_c' = design compression stress in distributed flanges (on total area).
f_t' = design tensile stress in distributed flanges (on total area).

$$\alpha' = f_c'/f_t'.$$

f_s = shear stress in skin due to torque.
k = coefficient to cover the additional area of stiffening stringers.
γ = density of material = constant.

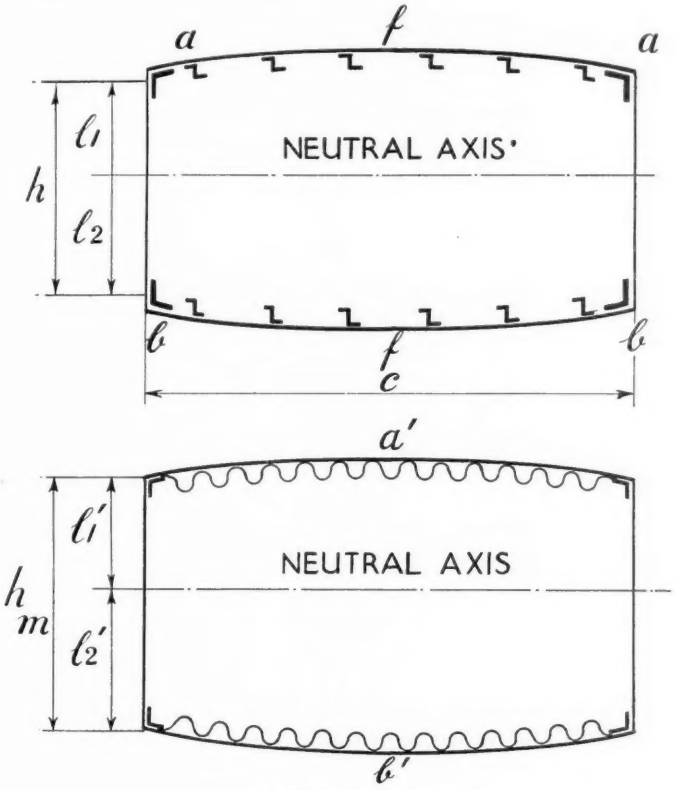


FIG. 24.

w_1 = measure of weight per unit length of flanges, skin and stringers.
w_2 = measure of weight per unit length of distributed flanges.
A = enclosed area of box section.
a' = area of top skin panel (distributed flange).
b' = area of bottom skin panel (distributed flange).

(*a*) *Concentrated Flanges.*

Considering that

$$I_m = 2\,a\,(a^2h^2)/(1+\alpha)^2 + 2\,bh^2/(1+\alpha)^2$$

it can be shown by quite elementary considerations that w_1 can be expressed by

$$w_1 = [\ \{\ BM\alpha\ (1+\alpha)/2\ f_c h\ \}\ (1+1/\alpha^2) + TCk/sA\ ]\ \gamma. \quad . \quad . \quad (i)$$

(*b*) *Distributed Flanges.*

Assuming that the moment of inertia of the total section

$$I_m' = a' l_{1m}^2 + b' l_{2m}^2$$

where l_{1m} and l_{2m} represent the mean distance of the main fibres on the compression side and the tension side from the neutral axis.

h_m = mean effective height of section and a' and b' the areas of top and bottom skin and stringers.

$$w_2 = [(BM/2\ f_c')\ \{\ \alpha'\ (1+\alpha')/h_m\ \}\ (1+1/\alpha'^2)]\ \gamma \quad . \quad . \quad (ii)$$

A weight comparison can be expressed by the ratio

$$w_1/w_2 = (f_t'/f_t)\ (h_m/h)\ [(1+\alpha)\ (1+1/\alpha^2)/(1+\alpha')\ (1+1/\alpha'^2)] + (T/BM)\ 2\ kf_t'/\ \{\ f_s\ (1+\alpha')\ (1+1/\alpha'^2)\ \} \quad . \quad . \quad (iii)$$

This expression represents a criterion in regard to the advantages of the two different structural methods from a mere weight point of view. It should be noted

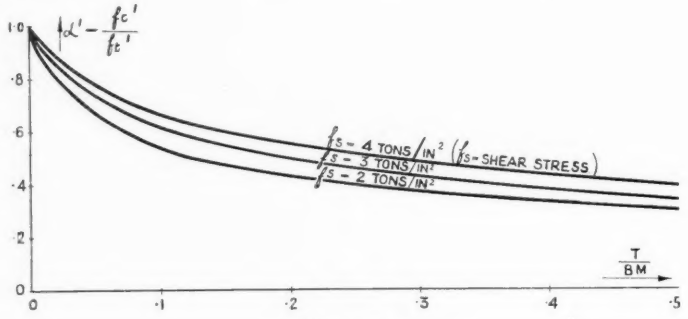


FIG. 25.

that it is independent of the actual dimensions except for the ratio of mean effective height to vertical distance between the spar flanges. It is also independent of the actual magnitude of the bending moment and the torque and depends solely on the ratio of the two. The most important parameters are α and α', *i.e.*, the ratios of compression to tensile stress for both types of construction.

With the ratio α' approaching the value of α the wing construction using distributed flanges scores decisively over the one with concentrated flanges. For example:—

$f_t'/f_t = 1$; $h_m/h = 1.16$.
$\alpha = \alpha' = 18/20 = 0.9$.
$f_t' = 20$ tons per sq. inch.
$f_s = 3$ tons per sq. inch.
$T/BM = 0.3$.
$w_1/w_2 = 2.554$,

i.e., the weight of concentrated flanges and skin becomes more than twice that for the stressed skin alone. This result is, of course, obvious and could have been fairly well predicted without a detailed investigation.

Of greater practical interest, however, is the question at which limiting values of α' the stressed skin type of structure becomes lighter than that with concentrated flanges. Solving equation (iii) for α' after introducing the following abbreviation:—

$$C = 1 - (f_t'/f_t)\ (h_m/h)\ (1+\alpha)\ (1+1/\alpha^2) - (T/BM)\ (2\ kf_t'/f_s)$$

leads to the following equation of the third degree in a':—

$$a'^3 + a'^2 \cdot C + a' + 1 = 0 \qquad . \quad . \quad . \quad . \quad \text{(iv)}$$

Example:—

$f_t' = 19$ tons per sq. inch.
$f_t = 25$ tons per sq. inch (extruded sections in hiduminium).
$h_m/h = 1.16$.
$f_t'/f_t = 19/25 = 0.76$.
$k = 1.48$.

In Fig. 25 are plotted the limiting values of a' for various ratios of T/BM with the shear stress f_s as parameter. Fig. 26 shows the distribution of T/BM and shear stress over a typical tapered wing of taper ratio 4. It follows that over the important portion of the wing a compression stress of more than

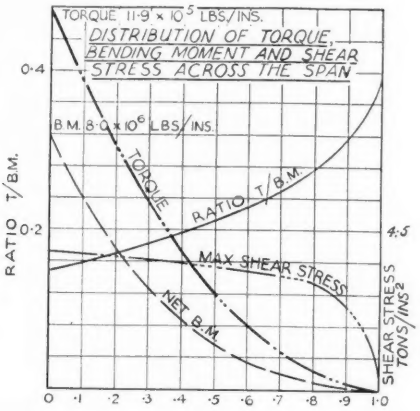


FIG. 26.

~ 8 tons/sq. inch for the outer portion of the wing and more than ~ 10 tons/sq. inch for the inner portion has to be obtained in stressed skin construction in order to achieve a saving in weight over a typical construction using concentrated flanges of extruded light alloy material. Such high overall compression stresses worked out on the total area of skin and stringers are only obtainable if a very efficient type of closed stringer or a very close spacing of spar stringers combined with close diaphragm spacing is adopted. The following table shows the results of test panels with typical skin stringer combinations:—

SKIN GAUGE	TYPE OF STRINGER	CROSS SECTIONAL AREA OF STRINGER INS²	STRINGER SPACING INCHES	RATIO STRINGER AREA: TOTAL AREA	DIAPHRAGM SPACING INCHES	f_c EFFECTIVE COMPRESSION STRESS TONS/INS²	f_c' MEAN COMPRESSION STRESS	f_t' TENSILE STRESS TONS/INS²	$f_c'/f_t' = \alpha$
20	20 S.W.G.	·0975	5·5	·576	6	15·0	15·0	18	·834
20			2·0	·318	17	13·4	8·6		·477
24			6·0	·442	17	12·8	7·55		·413
22	20 S.W.G.	·053	5·6	·240	16	13·4	6·75	18	·375
			1·0	·655	6	15·0	15·0		·834
22	22 S.W.G.	·06	4·25	·33	13	13·4	7·0	18	·388

MATERIAL
STRINGERS: DURAL (PROOF STRESS = 15·5 TONS/INS² ULTIMATE STRESS = 25 TONS/INS²)
SKIN: ALCLAD (" " = 13·5 " " " " = 24 " ")

The stressed skin type of construction therefore leads only to an advantage over the type with concentrated flanges if a skin highly efficient from the point of view of obtainable compression stress is employed. More efficient in this respect than flat skin with riveted on stringers is a combination of corrugated skin with flat skin.

A large series of tests carried out by Handley Page, Limited, yielded the following expression for the maximum permissible compressive stress in a

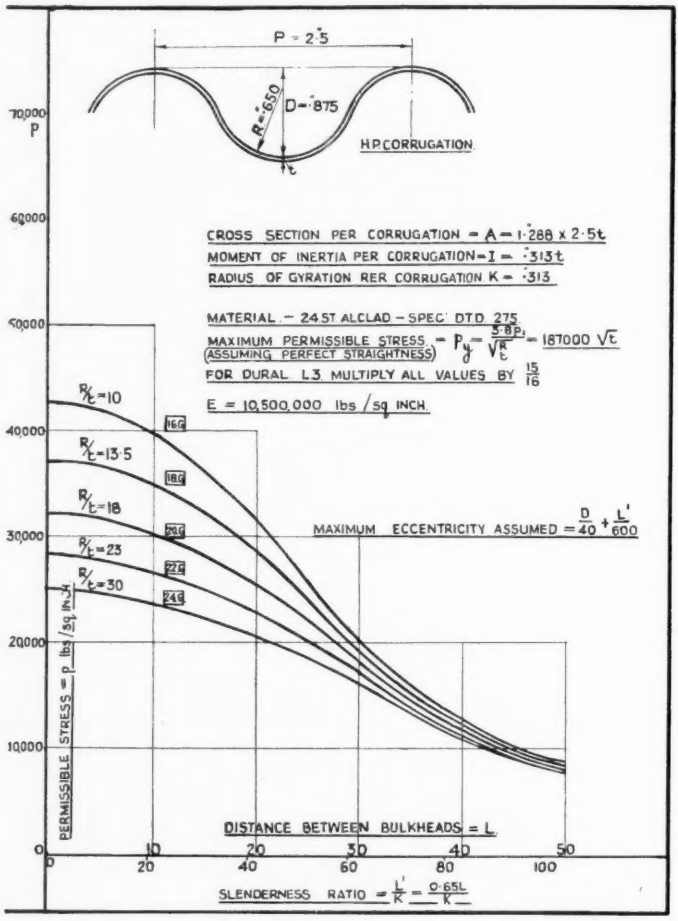


FIG. 27.

perfectly straight double-skinned panel:—

$$f_c = Kf_c'\sqrt{(t/R)}$$

where f_c' = 0.1 per cent. proof stress of the sheet material.
t = thickness of corrugated skin.
R = radius of curvature of the wave.
K = empirical coefficient.

The value of this coefficient depends on riveting pitch, ratio of flat skin to corrugated skin thickness and the pitch of the corrugation waves. For a very efficient combination this coefficient was found to be $K = 3.8$. Empirical results were found to lie closely on Southwell curves constructed on the following assumptions:—

$f_c' = 16$ tons/sq. in. (Alclad 24 ST. to Spec. DTD. 275).
δ = maximum crookedness of the corrugations $= D/40 + L'/600$ where
$D = 0.875$in. = height of wave.
L' = effective panel length = 0.65 of the total panel length between the flat ends (equivalent to a fixing value of 1.5).
K = radius of gyration = 0.313in.

These curves are plotted in Fig. 27. They reveal that with diaphragm spacings of 15/18in. design compression stress figures (based on the total area) can be reached for the heavier gauges equivalent to or closely approaching the proof stress of the material. One can therefore conclude that with a double skin a substantial saving in weight over the construction using concentrated flanges can be obtained. Even better figures are obtainable with hard rolled material of the RST class.

The advantage in regard to structural economy will be more pronounced for larger aircraft of an all-up weight $>$ 10 tons due to the thicker skin used.

3. Distribution of Shear Stress Across the Wing Section.

The above described general comparison is not quite complete. Apart from leaving out the effect of rib weight and shear web weight the shear stresses in the section resulting from other causes than pure torsion have not been considered. If we consider again a simple box consisting of two shear webs and two panels of reinforced skin, it is clear that the shear in the webs has to flow from the webs into the panels as indicated in Fig. 28. We call this shear flow the transfer shear.

The end load per inch applied to each stringer is represented by the difference in shear per inch to either side of the stringer.

If P_a = force acting on any particular stringer (including effective width of skin) at station a.
P_b = force acting at station b.
l = distance between a and b.
$(P_a - P_b)/l = S_1 - S_2 = \delta$
where S_1 and S_2 = shear in panels adjacent to stringer.

There will therefore be an accumulation of shear stress in the panel near the shear web and the shear will gradually drop off towards the centre of the panel. For a panel consisting of infinitely close stringers and neglecting elastic deformation of the section, the shear will fall off in a straight line. The actual distribution of shear in the panel has not yet been sufficiently explored according to my knowledge, but there is experimental evidence that in a box having a cross section of high aspect ratio the material at the centre of the box is less efficient than the material at the edges, which indicates that the actual shear distribution does not follow a linear law. Too widely spaced shear webs will lead to inefficiency of the structure, and additional shear webs are necessary in order to keep the aspect ratio of the area between the panels and two adjacent shear webs small (Fig. 29).

The accumulation of transfer shear near the shear webs requires strengthening up the skin beyond the thickness required to deal with the shear stresses due to torsion alone. When a combination of corrugated skin and flat skin is used, however, such reinforcing will usually be unnecessary as the corrugated skin is able to share the shear stresses with the flat skin.

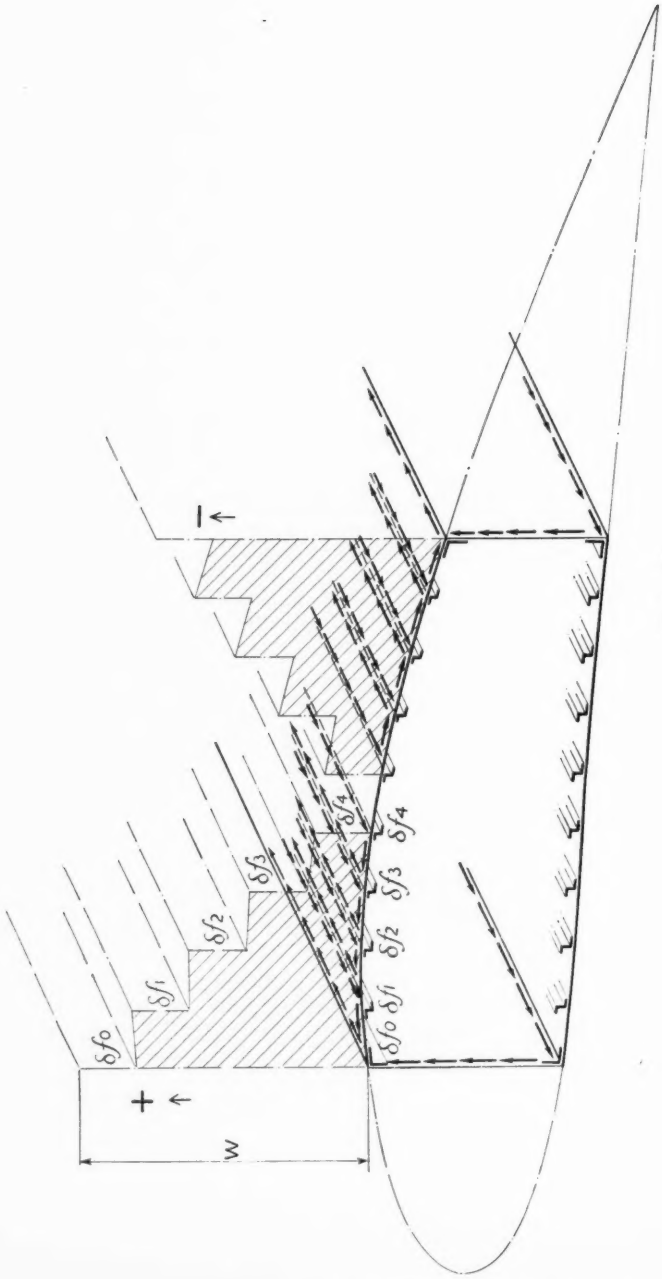


FIG. 28.

Apart from transfer shear the shear due to the anti-drag moment has to be taken into account. The combined shear distribution for two typical sections is shown in Figs. 30 and 31. The transfer shear is of the same order as the shear due to torque, but the shear due to anti-drag is of a smaller order. In the case of a double skin panel the resulting shear stress in the skin reduces the permissible end load stress to some degree, but the effect is not serious. With less efficient skin and stringer combinations the shear or the resulting tension field stresses may necessitate additional weight being put into the detail design of mutual attachment of the skin, flanges and ribs. The total effect is not fully explored yet.

4. Complete Weight Comparison between Two Wings of Different Construction.

General Characteristics of the Wings Compared.

Wing A.—This wing consists of a single spar with extruded flanges in hiduminium which take all the end loads resulting from bending. The skin covering extends to the flap hinge and the skin takes only shear.

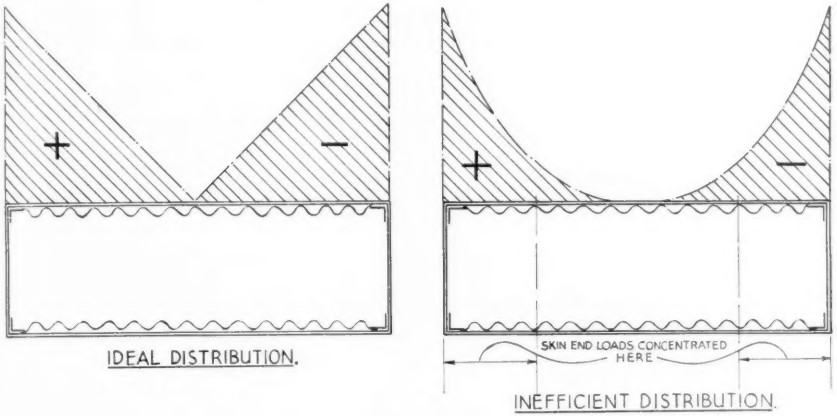


Fig. 29.

Wing B.—This wing has three shear webs and a fully stressed skin consisting of corrugated skin and riveted on flat skin.

Both wings were designed for the same very high factored wing loading, the same factored torque loading and the same all-up weight > 12 tons. They are identical in regard to net semi-span, mean chord and mean spar depth. The main design stresses for the two wings are contained in the following table:—

Wing A.	*Wing B.*
Design stress for spar flanges: Hiduminium.	Design stress for stressed skin: Aldural.
Mean comp. = 18 tons/sq. in.	Mean comp. = 12.5 tons/in.^{2} for outer wing and 14.5 tons/sq. in. for inner wing.
Mean tensile = 22.5 tons per sq. in.	Mean tensile stress = 19.5 tons/sq. in. for outer wing and 22.5 tons/sq. in. for inner wing (concentrated flanges).
Mean shear stress in skin 2.5 tons/sq. inch for outer wing and 4 tons/sq. in. for inner wing.	

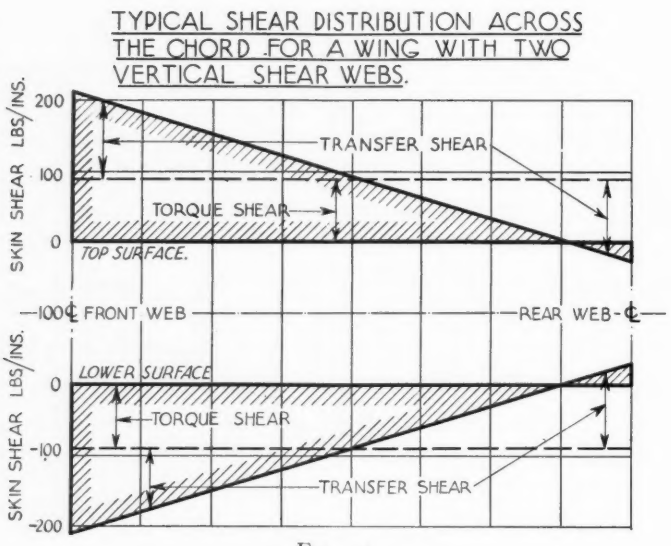


FIG. 30.

The result of the weight comparison is contained in the following table:—

Structural Component.	Wing A. Weight of Component in % of all-up weight of aircraft.	Wing B. Weight of Component in % of all-up weight of aircraft.	Difference. A—B.
Flanges and joints ...	6.72	7.84	+1.12
Webs	1.66	1.59	−0.07
Torsional member	3.51	0.646†	−2.864
Ribs	3.80	2.700	−1.1
Total primary structure ...	15.69	12.776	−2.914
Total secondary structure*	3.05	3.35	+0.3
Total structure	18.74	16.126	−2.614

A more general comparison of the weight of wing structures of certain British aircraft is contained in the following table:—

	Reduced for same all-up weight, span and load factors.		Aircraft of approximately the same factors, weight and span.		
Structural Component.	I. Two-spar wing with skin covering.	II. Single spar wing with complete skin covering	III. Multi-spar wing‡ (7 spars and skin covering).	IV. Single spar with Dural and fabric covering.	V. Box beam with distributed flanges and fabric covering.
	Percentage of all-up weight.				
Flanges and joints	6.46	4	9.95	4.26	4.26
Webs	2.24	1.7	2.46	1.71	2.63
Torsion Member ...	5.00	2.85	7.24	3.56	—
Ribs	2.00	5.80	1.70	4.62	2.87
Primary Structure ...	15.70	13.35	21.35	14.15	9.76
Secondary Structure	35	3.05	0.54	2.10	4.25
Total structure ...	16.05	15.45	21.89	16.25	14.01

* Includes weights of paint, nose portion, tail section, wing tips, aileron hinge bracket, flap linkage, ailerons, flaps and miscellaneous.

† Removable shear panels in inner wing.

‡ The relatively high structure weight of this wing is probably accentuated by a smaller taper ratio and a lower wing loading compared with the other two wings.

Conclusions.

This comparison confirms the conclusions of the general investigation. Although the weight for flange material is higher in the case of the wing with fully stressed skin, due to the lower overall stresses, this effect is more than offset by the fact that practically no additional material is required for the torsion

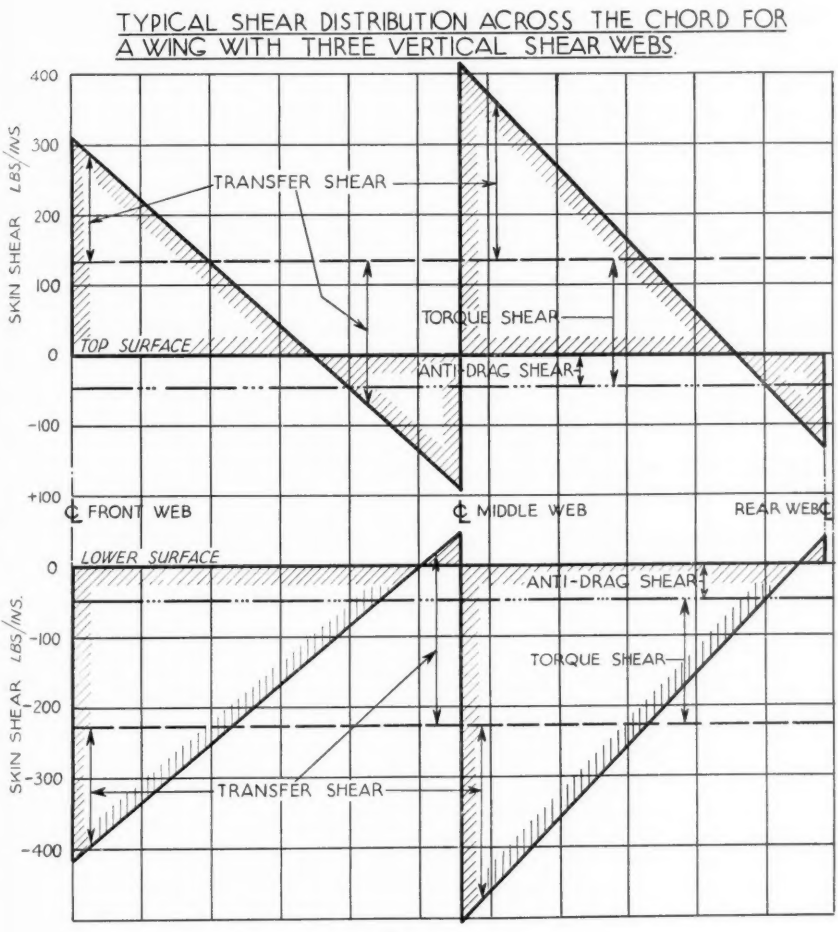


FIG. 31.

member. In addition, the ribs are a little lighter for the wing with fully stressed skin than for the wing with concentrated flanges.

The outstanding feature of the wing with stressed skin is the small amount of redundant material in the primary structure where redundant material is defined as such material which is not under all conditions fully stressed (excluding secondary structure which is approximately independent of the particular type of design), *i.e.*, redundant material = ribs + torsion member in the above table. The amount of redundant material amounts to a little over 3 per cent. of the

all-up weight of the aircraft for wing B while the corresponding figure in the case of the wing with concentrated flanges (A) is 7·3 per cent.

It seems hardly possible to reduce this figure (wing B) very much below this value, but it is possible to reduce the flange material represented by the skin by using a material of higher proof stress, for example, 24 RST in place of Aldural.

If we compare the wing employing a fully stressed skin with a wing where the most efficient spar (high grade steel flanges) is placed at the greatest depth of the section and where a highly efficient separate torque bracing is employed (no ribs and fabric covering). There are some small improvements possible in regard to flange weight, provided the design compression stress in the steel flanges exceeds a value of 60 tons/sq. in., but it seems likely that the redundant weight of the separate torque bracing (for a wing equal in torque stiffness to the stressed skin wing) plus the added weight of fabric will be more than 3.35 per cent. of the all-up weight and the saving achieved in regard to the spar flange material will therefore be nullified. At any rate, a possible weight saving can only be of a very small order.

This comparison reveals not only the shell type wing with fully stressed skin as a most efficient technical solution involving a minimum of redundant material and displaying the primary material in a very economical way, but also confirms a well-known mathematical law that near a minimum the changes are small.

Design Considerations other than Weight.

Considerations in regard to the structure weight are most important, but they are not the only ones which influence the decision of the designer. Single spar construction with concentrated flanges, for example, offers great advantages on small aircraft, taking into account the available space inside the fuselage at the point where the wing passes through the fuselage structure.

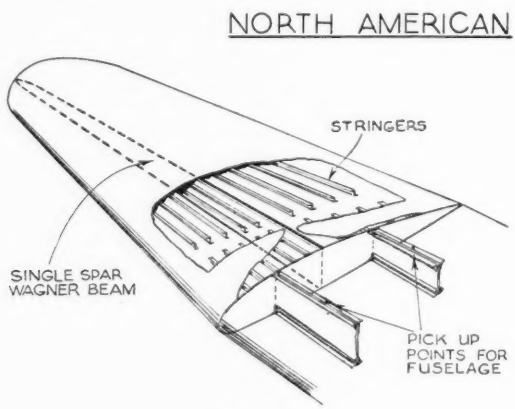


FIG. 32.

On single-engined aircraft the designer may often resort to a two-spar construction on the inner wing in order to stow the retracted undercarriage or tanks in a comfortable way. A typical example for this policy is the wing of the North American Corporation as shown in Fig. 32. Here we have a single shear web with distributed flanges consisting of skin and stringers for the outer wing. The single shear web transfers the shear into the two spars of the inner wing via a strong rib at the outer end of the inner wing.

Concentrated spar flanges are also of advantage in such cases where special attention has to be paid to quick detachability of the wings. With a single

spar wing, for example, a three point attachment is possible instead of peripheral flanges and a multiplicity of small bolts as are necessary for a stressed-skin type structure.

Last, but not least, we come to one of the most dominating design considerations, and that is the simplicity of manufacture and suitability for mass production.

Everybody concerned with the production of skinned metal aircraft knows that the most expensive operation in the construction of metal wings is riveting. Riveting is most expensive if it has to be done exclusively during the assembly of the wings on the job, partly because of the time spent in performing the riveting in inaccessible places of the wing, and partly due to the delay which is due to the limited number of workmen which can be employed for this operation. A great simplification and a general speeding up of assembly work is possible if the skin covering as a whole can be riveted up separately, preferably by machine riveters or employing spot welding, and if the wing can be assembled with the minimum amount of riveting done on the job. From this point of view the stressed-skin structure consisting of strong and easily transportable panels offers obvious advantages.

Conclusion.

In this review of the aerodynamic and structural features of tapered wings I have confined myself to such characteristics which have struck me as particularly important in the course of my own activities as a designer. The conclusions drawn have either supported a more or less preconceived design policy, or they are the result of reflections matured in the light of experience.

Summarising my personal views, I should like to state that I favour wings of fairly high taper ratio (not exceeding a taper ratio of 4:5) in view of their greater structural economy both from the point of view of strength in bending and stiffness against torque and also in view of the more efficient lateral control which the reduction in damping affords.

However, in using such high taper ratios and in benefiting from the advantages mentioned, special care has to be taken to maintain damping in roll and lateral control at the stall. In this respect I consider wing tip slots as the most efficient means known at present to prevent tip stalling of highly tapered wings and to avoid the ensuing effects.

Alternatively, of course, a lower taper ratio could be chosen and the wing then should be designed with combined increase of camber ratio and wash-out towards the tips, but this design will not be so efficient, or so controllable, or stable at the stall. There is no mystery in regard to the characteristics causing instability in the highly tapered wing. The de-stabilising effects can be countered by rational considerations applied to the initial design when fixing C.G. limits and the required tail volume.

As far as the structural solution is concerned, I am convinced that the fully-stressed shell type wing is superior to the still much favoured design with concentrated spar flanges. This is especially the case for aircraft exceeding an all-up weight of 10 tons, not only from a weight point of view but also in regard to efficient methods of production.

I consider that a rationally designed wing, using skin stressed up or nearly up to the proof stress, requires a minimum of redundant material for its primary structure and comes as closely to the ideal minimum structure weight as any other possible efficient technical solution.

My special thanks are due to the Air Ministry for permission to refer to certain still unpublished reports, and to Handley Page Limited for permission to present a number of technical data and in general to refer to the results of work evolved by their technical department; to *Flight* for their kind permission to reproduce Figs. 6, 7, 9, 19 and 20, and to various members of the technical staff of Handley Page Limited who have assisted me in the preparation of this paper, particularly to Mr. Lewin, Mr. Sandifer and Mr. Crean.

Appendix.

Relative Torque Stiffness and Skin Weight of Wings of Various Taper Ratio under the Assumption of an Isolated Torque (Aileron Reversal Speed Case).

General Assumptions.

Isolated torque T acting at mid aileron span $s' = 0.75\ s$ (Fig. 1).

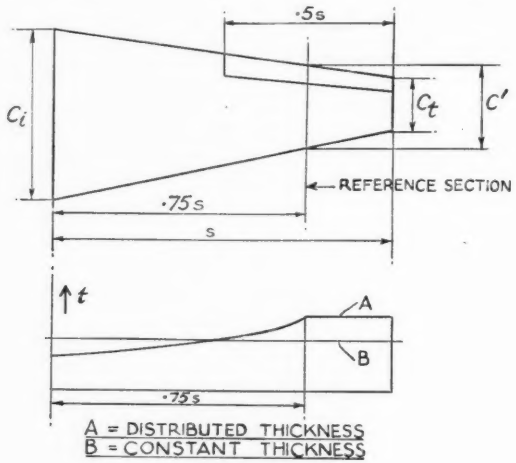


Fig. 1.

I. Distributed Skin Thickness, *i.e.*,

$$t_x = T_x / 2\,A_x f_s$$

where f_s = shear stress in skin = constant.

A_x = enclosed effective area of torque member.

$2A_x = K_0 \,.\, c_x^2$, where K_0 = const.

P_x = perimeter of torque member $= c_x \,.\, K_1$, where K_1 = const.

(*a*) Angle of twist.

$$\Theta = \int_0^{s'} (T/GI_D)\, dx \,. \qquad (1)$$

where

$$I_D = 4A^2/(P/t) = K_0^2 c_x^3 t / K_1$$

hence

$$\Theta = \{ (K_1 \,.\, f_s)/(G \,.\, K_0) \} \int_0^{s} (1/c_x)\, dx \,. \qquad (1a)$$

considering that

$$c_x = \lambda c_t - x c_t\,(\lambda - 1),$$

and

$$c_t = S_w/(\lambda + 1)\, s,$$

where S_w = total wing area.

λ = taper ratio.

s = semi-span.

c_t = tip chord.

and other symbols are the usual ones.

The evaluation of (2) gives

$$\Theta=(K_1f_s/GK_o)\ (\Lambda/4)\ \{\ (\lambda+1)/(\lambda-1)\ \}\log_e\{\ \lambda/(0.25\ \lambda+0.75)\ \} \qquad (2)$$

(*b*) Corresponding skin weight for skin inboard of reference section at $0.75\ s$:—

$$w_s=K_1\sigma\int_0^{0.75\ s} c\ .\ t\ .\ dx=(K_1\sigma T/K_of_s)\int_0^{0.75\ s}(1/c)\ dx$$

$$=(K_1\sigma T/K_of_s)\ (\Lambda/4)\ \{\ (\lambda+1)/(\lambda-1)\ \}\log_e\{\ \lambda/(0.25\ \lambda+0.75)\ \} \qquad (3)$$

where σ = density of skin material.

Λ = aspect ratio $=4s^2/S_w$.

f_s = shear stress.

Weight of skin for portion outboard reference section (assuming that t' = const. from $0.75\ s$ to s) :—

$$\Delta w_s=\sigma K_1\int_{0.75\ s}^{s} c\ .\ t'\ .\ dx=\{\ \sigma K_1T/K_of_s\ (c')^2\ \}\int_{0.75\ s}^{s} c\ .\ dx\ \ .\ .\ .\qquad (4)$$

where

$$\int_{0.75\ s}^{s} c\ \ dx=(S_w/32)\ \{\ (\lambda+7)/(\lambda+1)\ \}=\text{area of outside portion.}$$

Considering that

$$c'=\{\ S_w/4\ s\ (\lambda+1)\ \}\ (\lambda+3)$$

and

$$(c')^2=\{\ (\lambda+3)^2\ .\ S_w\ \}\ /\ \{\ 4\ \Lambda\ (\lambda+1)^2\ \}$$

Δw_s becomes

$$\Delta w_s=(\sigma K_1T/K_o\ f_s)\ (\Lambda/8)\ \{\ (\lambda+1)\ (\lambda+7)/(\lambda+3)^2\ \} \qquad (5)$$

Hence the total skin weight for one wing

$$W_s=w_s+\Delta w_s=(T\sigma K_1\Lambda/4\ K_of_s)\ (\lambda+1)\ [\ \{\ 1/(\lambda-1)\ \}\log_e\{\ 4\ \lambda/(2\ \lambda+3)\ \} + (\tfrac{1}{2})\ \{\ (\lambda+7)/(\lambda+3)^2\ \}\ ]. \qquad (6)$$

(*c*) Torque stiffness for a given skin weight.

$$m\Theta=T/\Theta.$$

For a certain skin weight W_s and for given values of σ, K_1, K_o, f_s and λ, the following value of torque T results in an angle of twist Θ at the reference section.

$$T=W_s/\ \{\ (\sigma K_1\Lambda/4\ K_o\ f_s)\ (\lambda+1)\ [\ \{\ 1/(\lambda-1)\ \}\log_e\{\ 4\ \lambda/(2\ \lambda+3)\ \} + (\tfrac{1}{2})\ \{\ (\lambda+7)/(\lambda+3)^2\ \}\ ]\ \} \qquad (7)$$

Hence the torque stiffness $m\Theta$ for a given total skin weight W_s becomes

$$m\Theta=16W_gK_o^2G/6K_1^2\Lambda^2\ (\lambda+1)^2\ \ \{\ [\ 1/(\lambda-1)\ ]\log_e[4x/(2\lambda+3)]\ \}^2 + (\tfrac{1}{2})\ \{\ (\lambda+7)/(\lambda+3)^2\ \}\ [\ \{\ 1/1/(\lambda-1)\ \}\log_e[4x/(2\lambda+3)]\ ] \qquad (8)$$

The relative torque stiffness $m\Theta'$ is

$$m\Theta'=16/[\Lambda^2\ (\lambda+1)^2]\ [\ \{\ [\ 1/(\lambda-1)\ ]\ \log_e\ [4\ \lambda/(2\ \lambda+3)]\ \}^2 + (\tfrac{1}{2})\ \{\ (\lambda+7)/(\lambda+3)^2\ \}\ \{\ 1/(\lambda-1)\ \}\log_e\{\ 4\ \lambda/(2\ \lambda+3)\ \}\ ]. \qquad (9)$$

II. Constant Thickness t.

$$t=T/2A_1f_s=\text{const.}$$

where

$$2\ A_1=K_oc_1^2;$$

c_1 = chord at wing root.

Hence

$$I_D=4\ A^2/(P/t)=K_oc^3T/K_1c_1^2f_s$$

and angle of twist

$$\Theta=(K_1c_1^2f_s/K_oG)\int_0^{0.75\ s}(1/c^3)\ dx \qquad (10)$$

considering that

$$c_t^3 = \{ S_w/s\,(\lambda+1) \}^3 = (4\,S_w^2)/\{ \Lambda \cdot s\,(\lambda+1)^3 \}$$

the integral in (10) can be expressed by

$$(3/32)\,\Lambda^2 \{ (\lambda+1)^3\,(5\,\lambda+3)/S_w\lambda^2\,(\lambda+3)^2 \}$$

or as

$$c_1^2 = (4\,S_w)/\{ \Lambda\,(\lambda+1/\lambda)^2 \}$$

one finally obtains

$$\Theta = (K_1 f_s/K_o G)\,(\tfrac{3}{8}) \{ [\Lambda\,(\lambda+1)\,(5\,\lambda+3)]/[(\lambda+3)^2] \} \quad . \qquad (11)$$

WEIGHT OF SKIN.

$$W_s = \sigma \cdot K_1 \cdot t \int_o^s c\,dx = \text{weight of total skin for one wing}$$

considering that

$$t = T/K_o c_1^2 f_s \text{ and } \int_o^s c\,dx = S_w/2$$

the weight becomes

$$W_s = (K_1\sigma/K_o f_s)\,(\Lambda\ T/8) \{ (\lambda+1)/\lambda \}^2 \quad . \quad . \quad . \qquad (12)$$

Hence the torque absorbed by a given skin weight $W_s =$

$$T = \{ 8 W_s K_o f_s \} / \{ \sigma K_1 \Lambda\,[(\lambda+1)/\lambda]^2 \} \quad . \quad . \quad . \qquad (13)$$

and the torque stiffness

$$m\Theta = (T/\Theta) \{ (64\,W_s K_o^2 G/3\,K_1^2 \Lambda^2 \sigma) \} (\lambda+3)^2/[\{ (\lambda+1)/\lambda \}^2 \{ (\lambda+1)\,(5\,\lambda+3) \}] \qquad (14)$$

or the relative torque stiffness

$$m\Theta' \sim 64\,(\lambda+3)^2/3\,\Lambda^2\,[\{ (\lambda+1)/\lambda \}^2\,(\lambda+1)\,(5\,\lambda+3)] \quad . \qquad (15)$$

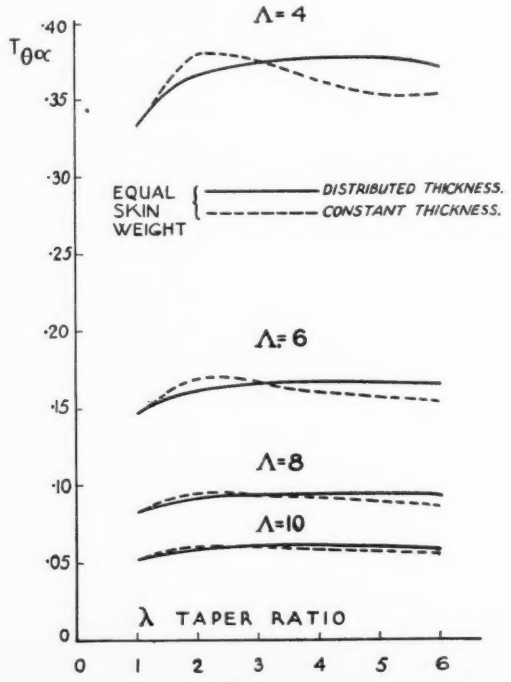


FIG. 2.

In Fig. 2 curves are plotted illustrating the effect of taper and aspect ratio on the relative torque stiffness for constant and distributed skin thickness. Varying the skin thickness along the span only offers a slight advantage for taper ratios > 3 and for relatively low aspect ratios. For taper ratios < 3 constant thickness gives greater torque stiffness for the same skin weight under otherwise equal conditions. For aspect ratios > 6 there is little to choose between the two methods whatever taper ratio is adopted.

It should be remembered that this comparison is based—as far as the distributed skin thickness is concerned—on the assumption that the skin thickness varies from wing root to the reference section situated at 0.75 and remains constant from there on to the outer tips. This is a somewhat arbitrary but practical assumption.

A comparison in regard to torque stiffness for a given skin weight which only takes into account the skin weight inboard of the reference section supplies a somewhat different result (see Fig. 3). On this basis distributed skin thickness would give a definite advantage in regard to torque stiffness as compared with a wing where the same skin weight is spread with constant thickness.

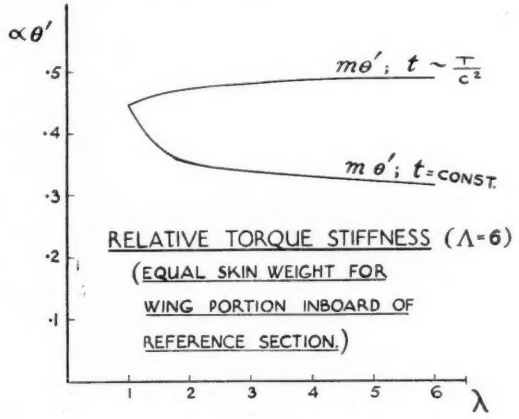


FIG. 3.

The curves for relative torque stiffness in diagram can be used for a rapid determination of skin weight and thickness required to satisfy the requirements in connection with aileron reversal speed.

EXAMPLE.

$v_{Kr} = 690$ ft./sec. (aileron reversal speed).
$S_w = 660$ sq. ft.
c_m = mean chord.
$\sigma = 174$ lbs./ft.^{3}.
$K_0 = 0.12$.
$K_1 = 1.24$.
$G = \frac{2}{3}$ 0.4 GE. The factor $\frac{2}{3}$ takes into account the effect of waving.
$\rho = 0.00176$ = air density at 10,000ft.
K = aileron reversal speed coefficient.

The values to be introduced for K are based on figures given in R. and M. 1568, assuming an aileron span of 0.5 s and a constant aileron chord of 0.25 c.

$$v_{Kr} = K\sqrt{(m\Theta/\rho s c_m^2)} \quad . \quad . \quad . \quad . \quad (16)$$

$$m\Theta = v_{Kr}^2 \rho s c_m^2 / K^2 = \{ (W_s K_o^2 G) / (K_1^2 \sigma) \} m\Theta'$$

where $m\Theta'$ = relative torque stiffness according to (15) or Fig. 2.

Hence the weight of the skin for the torque member will be

$$W_s = (K_1^2 \sigma / K_o^2 G m\Theta') (v_{Kr}^2 \rho s c_m^2 / K^2) \quad . \quad . \quad . \quad (17)$$

and the skin thickness required

$$t = 2 W_s / K_1 \sigma S_w = (2 v_{Kr}^2 \rho s c_m^2 K_1) / (S_w K^2 G m\Theta' K_o^2) \quad . \quad . \quad (18)$$

In Fig. 4 the resulting skin weight W_s, according to the above numerical assumptions, has been plotted as a function of taper and aspect ratio. These curves clearly indicate again the advantage of a fairly strong taper; however, little is gained by exceeding a taper ratio of $3 \div 4$ for aspect ratios $\Lambda \leqq 6$.

The effect of aspect ratio on skin weight is most pronounced. Increasing the aspect ratio from 6 to 10 more than doubles the skin weight, a fact which speaks rather against the use of high aspect ratios on very fast aircraft.

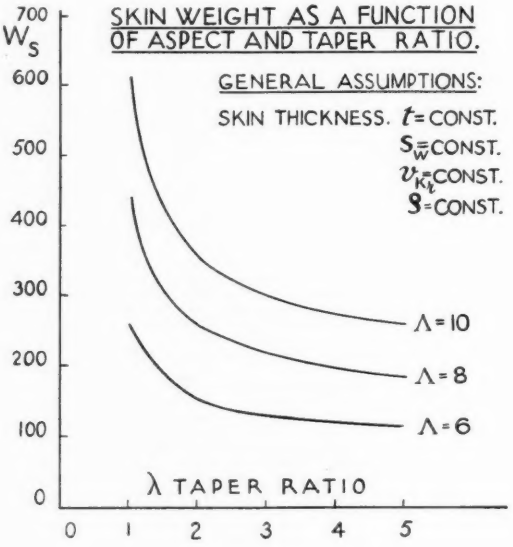


FIG. 4.

Another point is worth mentioning. It follows from (18) that on otherwise equal conditions the skin thickness required is proportionate to v_{Kr}^2. With the figures of the above example and assuming a taper ratio of 4.2 and an aspect ratio of 6, the skin thickness works out to be 0.0198 or $\sim 25\ G$.' Supposing the aileron reversal speed is increased by 41 per cent., the thickness must be doubled, *i.e.*, 19 G has to be used. This indicates that a wing construction, where a separate torque member is employed whose material does not contribute to the flexural strength, becomes increasingly inefficient as diving speeds go up in comparison with a construction where the flange material of the spar is distributed, thus supplying the top and bottom walls of a very stiff torque structure.

Finally, in view of certain discussion remarks, the effect of strength and stiffness requirements on skin thickness has been investigated.

From a strength point of view the skin thickness is determined by

$$t = T/2\,Af_s = [\int_0^s \{\, c^2 C_m\,(\rho v^2/2)\,n dx \,\}\,]/(K_c c^2 f_s)$$

where C_m = moment coefficient.
v = speed in a fast glide.
n = load factor.

Dimensions of the wing :—

$S_w = 668$ sq. ft.
$s = 32$ft.
$\lambda = 3$.
$\rho = 0.00176$ (10,000ft.).
$n = 2.2$.
$K_c = 0.12$.
$f_s = 3.5$ tons/inch^2 and 5.5 tons/inch^2.

Assumptions in regard to speeds and C_m :—

I. $v_1 = 575$ ft./sec. $= 392$ m.p.h.
$vK_{r1} = 1.2 \times v_1 = 690$ ft./sec. $= 470$ m.p.h.
$C_{m1} = 0.049$.

II. $v_2 = 660$ ft./sec. $= 450$ m.p.h.
$vK_{r2} = 1.2 \times v_2 = 790$ ft./sec. $= 540$ m.p.h.
$C_{m2} = -0.045$.

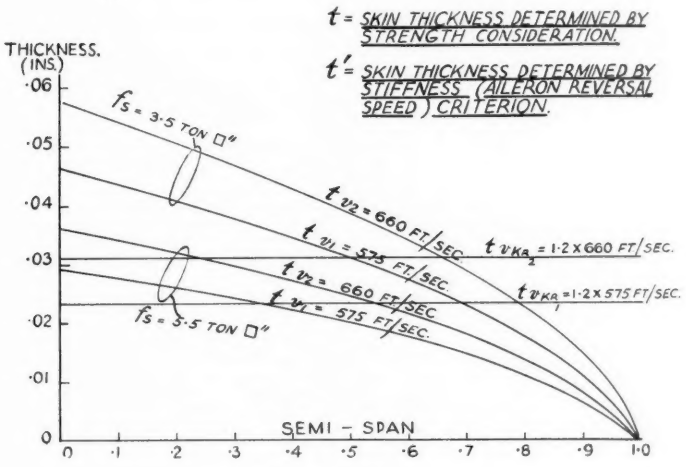

t = SKIN THICKNESS DETERMINED BY STRENGTH CONSIDERATION.
t' = SKIN THICKNESS DETERMINED BY STIFFNESS (AILERON REVERSAL SPEED) CRITERION.
THICKNESS. (INS.)
·06
·05
·04
·03
·02
·01
0
f_s = 3·5 TON □"
t_{v_2} = 660 FT/SEC.
t_{v_1} = 575 FT/SEC.
t_{vK_2} = 1·2 x 660 FT/SEC.
t_{vK_1} = 1·2 x 575 FT/SEC.
t_{v_2} = 660 FT/SEC
t_{v_1} = 575 FT/SEC.
f_s = 3·5 TON □"
SEMI - SPAN
0 ·1 ·2 ·3 ·4 ·5 ·6 ·7 ·8 ·9 1·0

FIG. 5.

The results are plotted in Fig. 5 showing the distribution of torque and skin thickness as required by strength and stiffness criterions. It becomes obvious that for such aircraft, where the speed in a fast glide is limited to 1.5 times the value with normal r.p.m., the strength requirement determines the skin thickness over the major portion of the wing,* especially if the shear stress is limited to a relatively low value. With increasing diving speeds the stiffness criterion affects an increasing portion of the wing until it becomes finally the decisive criterion in case of extremely high diving speeds.

* It is appreciated that this flight condition is not always a decisive strength criterion.

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Discussion.

The President (Mr. H. E. Wimperis) : He complimented Dr. Lachmann upon the very interesting and complete manner in which he had dealt with the complicated problem of the behaviour of tapered wings, which, with the flap additions necessary to allow for a high wing loading, was one of the most controversial and difficult problems of the day.

Mr. F. Handley Page (Vice-President): Dr. Lachmann had dealt very ably with the many points that affected design, with regard to controllability, stability and weight, following the change over to the monoplane; and in going into those details he had shown how essential it was to analyse down to their bases all the many things that had been brought into design by reason of that change. They needed a great deal more data, and Mr. Handley Page urged that all engaged in design should publish details in regard to designs, so far as they were allowed, so that they could accumulate knowledge of monoplane design quickly, now that the change had come about, because, quite apart from those basic questions of controllability, stability and weight, they must design machines that could be made. A great many people produced designs which were extraordinarily good in the drawing office, but when their designs came down to the works the comments of a great many of the workmen as to the abilities of people, who might be efficient with slide rules and who knew all about Kx and Ky, to design something which could be made were not such as one could repeat at a meeting of the Royal Aeronautical Society. It was necessary to disseminate basic knowledge in regard to monoplanes, so that with the aid of that knowledge the designers could design something really practicable. He hoped speakers in the discussion would be able to give an outline of the information they were going to publish subsequently at great length through written contributions!

Mr. C. C. Walker (*Fellow*) : His firm had noticed that on tapered wing machines it was possible to secure improved lateral qualities, not by altering the camber of the centre line along the wing, but by altering the curvature of the top surface and the bottom surface in such a way as to keep the mean camber line the same. That had been done on the assumption that the curvature of the top surface was the factor which regulated everything with regard to the flow of air over the wing so far as stalling was concerned, and it certainly met with a fair measure of success, though to a variable extent in different aeroplanes. He asked if Dr. Lachmann's curves dealing with the position of the maximum ordinate in the wing were the results of observation and experiment, or of calculation. He personally had made some very interesting observations on a far forward ordinate, but he had not time at that meeting to discuss it in detail.

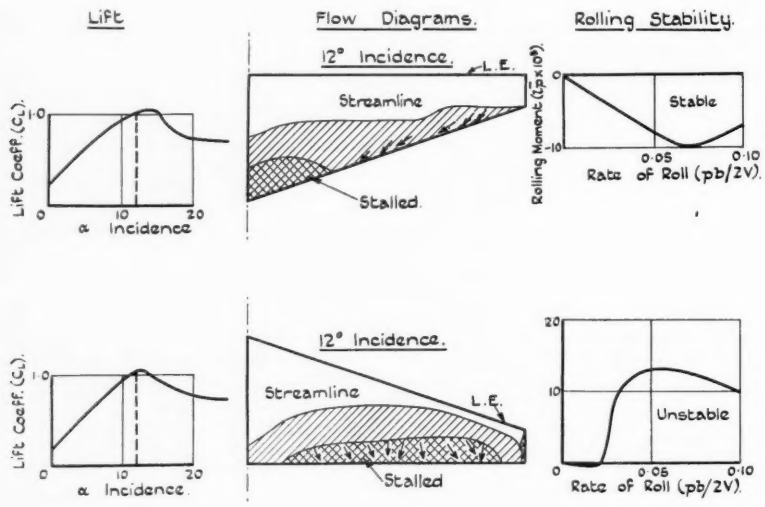
In comparing the weights of two kinds of construction, *i.e.*, the box beam and the stressed skin, presumably Dr. Lachmann had taken equal torsional strength. One wondered, however, whether that meant necessarily equal torsional stiffness, which was a more important criterion than torsional strength.

Mr. H. B. Irving (National Physical Laboratory, *Fellow*) : He congratulated Dr. Lachmann upon a masterly paper and upon his courage in preparing it at a time when their knowledge of tapered wings was in such a state of flux.

Mr. Irving amplified, by means of a diagram, the reference made by Dr. Lachmann to an experiment carried out at the National Physical Laboratory (in connection with the stalling of tapered wings) on the effect of sweep forward and sweep back of the trailing edge.

The figure related to experiments on two wings, both of R.A.F. 38 Section (uniform section along the whole span) and both of 4/1 taper. The first had its leading edge straight, *i.e.*, at right angles to the plane of symmetry, and in the other it was swept back. The middle diagrams of the slide were obtained from observations of the behaviour of wool tufts on the upper surface, after the manner adopted first by Flight-Lieut. Haslam on the full scale. The unshaded portion indicated streamline flow, and the cross-hatched portion indicated the

stall. In the other portion there was rather disturbed flow, which could hardly be described either as stalled or as unstalled. On the left of the slide there were lift curves for the two wings (lift against incidence), and the dotted lines showed the incidence to which the diagram applied (12°). On the right of the slide was a rolling stability diagram, where the rolling moment was plotted against rate of roll, the rate of roll being comparatively slow. Where the curve was below the line there was stability in roll, and where it was above the line there was instability. First one should note the general characteristics of the stall. In the swept forward wing the stall was beginning at the centre, and diagrams obtained for different angles of incidence showed that that stall gradually spread forward and outward. In contrast to that, on the swept back wing the stall actually began at about two-thirds of the way out and gradually spread forward, outward and inward. The arrows on the diagrams showed the general direction of the flow; and Mr. Irving drew attention to the very strong inward flow near the trailing edge of the swept forward wing, a factor to which Dr. Lachmann had referred in his paper. Flow of that nature had been observed quite independently by Mr. W. E. Gray, first on a model, and then he had demonstrated that it



occurred also on the full scale. On the swept back wing there was a slight outward tendency, but it was not nearly so marked as was the inward tendency on the swept forward wing. Mr. Gray had put forward a theory to explain the significance of the inward flow, but whatever the merits of the theory there seemed no doubt that the effect was a transference of air in the boundary layer from the tip towards the centre, which seemed to result in delaying the stall at the tip and accentuating the stall at the centre.

The diagram for the incidence of 12° showed up in marked contrast the effects of sweep back and sweep forward. But one must guard against reading too much into the diagram as to the relative merits of the two wings. One would be inclined to say off-hand that the swept forward wing was the good one and that the swept back wing was the bad one; and he believed that that was so, to a certain extent. But if the experiments were carried to higher angles of incidence one found that the swept forward wing became unstable in roll very soon after the 12° incidence, at only about $1\frac{1}{2}$° later than the swept back wing. So that one

must not make hasty conclusions as to the lateral stability of the two wings at low speeds, but must await full scale experience.

It was possible, by keeping the leading edge straight, and the aspect ratio the same (7.2), to go to a taper of about 9/1 without premature wing tip stalling; but if the aspect ratio were increased so that there was not as much sweep forward on the trailing edge one began to find a portion near the tip stalling at the same time as a portion near the centre.

Mr. W. E. GRAY: He had hoped to show a slide indicating how in the case of a small Monospar machine a stalled region could apparently suck air away from an unstalled region. The flow over the aileron surface was bent inward parallel to the trailing edge almost simultaneously with the commencement of the stall, which occurred first just inboard of the aileron. That perhaps explained some of the high aspect ratio American wing stalling, where wings stalled in patches along the span.

Reference to the American rolling criterion had been made by Dr. Lachmann, who had accepted their figure of 0.075 as satisfactory; that was so in 1931, but in 1933 the Americans had changed their minds and had written it down to 0.045 in the tunnel and 0.030 in free flight. He asked whether they had since changed their minds again.

It would be interesting to hear from Dr. Lachmann any known reason why a yawed tapered wing, or for that matter a yawed parallel wing, stalled first at the down-wind end.

With regard to the statement that the theory which he (Mr. Gray) had put forward was unconvincing, he asked if Dr. Lachmann would elaborate that and would give some reason for saying, as he had said in the paper, that the spanwise component of the flow would affect the boundary layer, especially when the aerofoil was stalled. With regard to the lecturer's statement that dead air would be transported inwards in the case of a swept forward trailing edge, he asked whether that was based on the evidence so far collected by the speaker or whether Dr. Lachmann had some theoretical reason for it. Mr. Lock had regarded the matter in a rather different way and had visualised the flow as split up into components parallel to the span and across the aerofoil. Having discussed the matter with Mr. Lock, without having reached any particular agreement. Mr. Gray had since carried out further tunnel tests and had found that even at quite considerable distances above the wing there was a lot of bending in the flow, which was more or less in agreement with Mr. Lock's ideas; but Mr. Gray believed that that could be explained by transverse pressure gradients and that the two views perhaps did not conflict.

Mr. W. E. PETTER (*Associate Fellow*): He found it rather difficult to understand the reference made to the ease of production of the stressed skin wing as compared with the single spar wing, because, as Dr. Lachmann had shown, stringer spacing on a stressed skin wing had to be of the order of 3in. or 4in., so that it was necessary to have a row of rivets at every 3in. or 4in. if the skin were to be at all efficient; whereas if the skin were treated merely as a torsion and drag member, and if a single spar were used, the jointing of the skin at intervals of 12in. was quite satisfactory. So that the riveting was reduced in the ratio of 3 : 1 by using the single spar wing, and although admittedly it might be heavier in large aircraft, in the case of small aircraft, with the engine nacelles, fuselage, petrol tanks, etc., cutting the skin about, it was probably equally as efficient as the fully stressed skin construction.

Referring to the longitudinal stability curve for the low-wing monoplane, shown by Dr. Lachmann, he said that the de-stabilising effect of the nacelles was extraordinarily interesting, and he wondered whether a designer, instead of pushing the engines forward in order to render the aeroplane more stable, as was thought, would do better to keep the engines back, at the same time reducing surface area and possibly obtaining a more efficient propeller, and if necessary increase very

slightly the tail volume. Some work on nacelles of two or three different lengths, in relation to the stability of monoplanes, would be extremely interesting.

The aircraft industry was bound to become interested more and more in securing the maximum of lift from smaller and more complicated wings, and it owed a great deal to Dr. Lachmann and to the Handley Page Company for having published the information (which Mr. Petter could substantiate from his Company's experience) that a tip slot on a tapered wing, with a partial span flap, was definitely a contributor to lift at reasonable angles of incidence. A good deal of time had been devoted, in this country and abroad, in the endeavour to employ a full span flap, with all the complications of new lateral control devices, but it seemed much simpler to secure the extra little bit of lift from the tip by using a tip slot in combination with a partial span flap and a normal type of aileron. He had no detailed full-scale figures, but the full-scale work, so far as it had proceeded, seemed to confirm the results obtained in the wind tunnel and the figures given by Dr. Lachmann, that roughly 20 per cent. increase of lift at reasonable angles of incidence could be obtained with tip slot and partial span flap.

Mr. Hollis Williams (*Associate Fellow*): His Company had flown two types of tapered wing, each of them having about the same amount of taper, but one having a straight leading edge and the other having the leading edge swept back $25\frac{1}{2}°$. The construction of the swept back type had been embarked upon with some trepidation, in view of known wind tunnel results, but it was a necessary feature to secure reasonable load distribution. However, when the machine was flown and compared with the straight leading edge type, it was found that both aircraft complied with the requirements of A.D.M. 293 (behaviour at and near the stall) equally well.

His conclusion, therefore, is that there is no need to be afraid that viscous tendencies would be developed by the swept back wing, provided that adequate care is taken to avoid premature stalling of the tips by suitable aerodynamic twist.

The paper by Dr. Lachmann, although already exceedingly comprehensive, could be made even more comprehensive if it were related to the question of cost —to which Mr. Handley Page had referred. From a comparison of wing structures made by Dr. Lachmann (leaving out one notable exception, which was a very heavy wing), the weight difference between them all was about 200 or 300 lbs., on a total weight of 10,000 lbs. for the whole machine, *i.e.*, 2 or 3 per cent. whereas in respect of cost, the differences might be very much greater.

With increasingly high wing loadings the effect of type of wing structure on total weight will shrink still further, and the selection must be made therefore almost entirely with reference to production cost.

Mr. P. P. Nazir (*Associate Fellow*): With reference to a method he had developed for changing the tip stall on sharply and moderately tapered wings into an intermediate or spread stall, by using a suitably cut slot through the wing, he would like to make the following comments. The tip stall upon tapered wings, set in from the back of the wing, and the cut slot, seemed to cure or delay the stall just where required, and it was useful even up to an incidence of 40°. Further, the cut slot could be employed very successfully in connection with flaps used either for slow landing or for lateral control.

He had been developing the system both on rectangular and on tapered wings, and the improvement of efficiency was just as great, or even greater, on the tapered wing, as compared with the rectangular wing. Mr. Nazir found it possible to make the lift side aileron even more powerful at high incidences, than the drag side; contrary to any of the present-day devices in use. His device he said might also make it possible to suck the boundary layer from the back of the wing without any complications.

Mr. F. RADCLIFFE (*Associate Fellow*): With reference to Fig. 12, in which a comparison was made of aerofoils 4412 and 2418, he said that since stalling was under consideration it would be natural to have the flaps down on a modern aeroplane, and in that case the argument put forward by Dr. Lachmann seemed to require some modification. He asked for Dr. Lachmann's views of the matter.

His experience of a limited number of types of monoplanes confirmed that put forward in Section II, 5 (b) of the paper, regarding the more forward C.G. position for monoplanes.

The maximum C_L values developed by various wing arrangements, as mentioned in Section II, 6 (*f*), were presumably for "engine off" in every case. It was interesting to note that if the slipstream effect were taken into account one could reckon on an additional 0.8 C_L being obtained from that slipstream effect over the wings, particularly in the case of twin-engined aircraft.

Mr. J. C. STEVENSON (*Associate Fellow*): Could Dr. Lachmann explain further his analysis of the comparative weights of the two wings *A* and *B* by developing the point with regard to the high factored loading he specified for the particular machine? He was a little surprised by the order both of the total wing weight percentage and of the item termed "total secondary structure weight."

With regard to the reference to longitudinal stability and the definition of the rearmost C.G. limit for stability, Mr. Stevenson asked if there was not also a condition governing the most forward limit. If the normal C.G. were brought still more forward with respect to the mean aerodynamic chord, what limit would there be to extra forward movement to preclude instability of possibly another nature?

Concerning the apparent effect of sweepback of the leading edge on the lateral stability characteristics, when this expedient is so often necessary for correct location of the C.G., one might derive some comfort from the remarks of Mr. Hollis Williams in the matter of the full scale evidence on the straight leading edge, and swept back leading edge. This problem was one which must be worrying quite a number.

Mr. D. SHARMAN: Is the efficiency of the present-day monoplane increased and would the monoplane exhibit better lift characteristics as the result of the use of the retractile auxiliary wing devices, as proposed by Dr. Schmeidler in Germany and by Miss MacDonald in this country?

Dr. ROXBEE COX (*Fellow*): He was interested in Dr. Lachmann's statement that "the skin thickness is assumed to be thinned down along the span proportionate to the decrease in torque." The inference from this is that the skin thickness is decided by strength considerations, for stiffness considerations based on the application near mid-aileron of an isolated torque would tend to produce constant thickness over most of the span on the theory to which Dr. Lachmann refers. Is this inference correct?

It should perhaps be pointed out that the statement quoted above is only strictly true for a wing of constant section. For a tapered wing, if the Bredt-Batho formula is assumed to apply (a doubtful assumption except for small tapers), the minimum strain energy condition appears to lead to thickness varying as the resultant torque divided by the enclosed area of the section.

He was interested in Fig. 5 of the paper, which exhibits the increase of wing structure weight with aspect ratio. Dr. Lachmann has decided that there is little point in adopting taper ratios greater than 4: 1, and he would like to know whether he has considered the companion problem of the practical economic aspect ratio. He ventured to suggest that it might prove unexpectedly small.

In comparing the weights of different forms of wing construction, he considered that Dr. Lachmann showed considerable temerity, and he was sorry to find that he was not seriously challenged. As his (Dr. Roxbee Cox) views are substantially in agreement with the lecturer's he cannot supply the attack which he felt

should have been launched. There are, however, some points on which he considered he should be asked to comment:—

(a) Comparison of the weights of different constructions on the basis of simplified models such as those of Fig. 24 must be regarded with suspicion. They are true for the models but may not be true for real wings. Real wings may need to have holes in them, or to fulfil other conditions inimical to the distributed flange system, and it may well be in some cases that the concentrated flange design is superior to the distributed flange design. Dr. Lachmann cites a particular example in which the distributed flange wins. Cannot another designer produce an example illustrating the opposite? He felt that particular requirements, at any rate in military machines are apt to swamp the theoretical advantages about which it is so fascinating to argue.

(b) In a table which he showed on the screen, Dr. Lachmann compared the weights of different forms of wing construction. He felt that this comparison to be effective needs some statement about its basis. He found it difficult to believe that the multi-spar wing could possibly be so bad in comparison with the others. Are not the examples taken from machines of very different sizes? If so, has allowance been correctly made for the size in reducing to a common basis? If the Northrop multi-web type of wing is regarded as a multi-spar, he could assure Dr. Lachmann that on any basis of comparison it is light.

Mr. W. R. Andrews: Dr. Lachmann has treated very thoroughly the question of the aerodynamic loading on a tapered wing in the unstalled condition. His conclusions are, as the wing is tapered the stall tends to start first at the tip. On purely theoretical grounds his reasoning, of course, is quite beyond dispute, but it seemed to him that the question is more involved and cannot be wholely covered by mathematical reasoning. Mr. Walker has drawn attention to the fact that the stalling of one of his machines was improved by a change of thickness at the wing tip. Furthermore, it is well known that certain biplanes with constant chord wings have been known to stall violently at the tip at zero rate of roll, which is contradictory to the theoretical argument.

It would seem that the aerofoil section has a great influence upon the question of tip stalling, and from the evidence of tests made in the variable density wind tunnel, the radius of the nose is of as much importance as anything else in determining the shape of lift curve at and beyond the stall. As the thickness ratio is reduced the nose radius, as a fraction of the chord, should increase. It is realised, of course, that no amount of change of the radius of the nose of the aerofoil can stop the inevitable stall as the taper is made large, but the method outlined suggests a means of reducing to the minimum the possibility of a premature tip stall for a given taper.

There is another point which is of importance at the present time, when the low wing monoplane is so much to the fore, and that is that the stability of the low wing arrangement deteriorates at slow speeds as compared with that of the high wing. This does not mean that all the low wing arrangements are unstable at the stall but rather that the low wing arrangement is less stable at the stall than with the high wing. What may be taken as a vicious stall in the case of the low wing monoplane may be partly due to the machine entering an unstable region, which will magnify the stall more than if the same wing had been fitted to a high wing monoplane.

Mr. E. E. Blount: He was interested to note the statement that the relative merit of distributed flange wings and concentrated flange wings depends only upon the *ratio* of applied torque to bending moment, not upon the absolute magnitudes of these quantities. So it would appear from the equation. But he thought it would be found that the absolute value of the bending moment, governing as it does the quantity of flange material needed, would have a direct effect upon the allowable stress developed in a distributed flange and thus introduce its influence into Dr. Lachmann's equation through the term f'_c. If a great deal of

flange material is needed, it will be easy to design stringers of such proportions that a very high allowable stress is obtained, and they may be spaced so close together that a considerable additional stress is developed in the flat skin between. But if very little material is needed, the stringers will be of such light construction and so far apart, that only low stresses may be developed in them and the concentrated flange type has the advantage. If corrugated sheet is used in the distributed flange type, this effect is represented by a thinning of the sheet and poor R/t values. The choice between corrugated sheet and flat-sheet-and-stringers for the distributed flange type is also greatly affected by the amount of flange material required, for corrugated sheet is essentially a series of stringers joined together along their edges, and it is only when much material is required that such close spacing will be economical. Within reasonable limits, the magnitude of the wing torque, either relative or absolute, has no effect upon the choice between concentrated flanges and the flat-sheet-stringer type since the most economical application of the latter includes using a skin of the minimum practical thickness the same as for concentrated flanges. If high bending moments are involved, the corrugated sheet distributed flange type may prove superior by virtue of making use of the greater wing depth between spars and eliminating much secondary structure, without regard to the shear area requirements, great or small, imposed by the wing torque.

Dr. Lachmann very ably pointed out the advantage of a tapered wing in supplying spar depth where the bending moments are high and it is most needed. In very large airplanes, heavy quantities of gasoline or other useful load may be placed so far out in the wing as to cause the bending moment from that point inward to increase only very slightly. Torsion may also be greatly reduced. Thus the advantages of taper from such a point inward have largely disappeared, and an inner panel of uniform thickness may prove desirable.

Mr. W. E. Gray (*Communicated*) : On the structural side, he would like to ask Dr. Lachmann whether there is any added torsional load imposed on a tapered wing when swept back, or forward, merely because of the sweep. He asked that because a designer of considerable experience recently told him that there is an added load, and he was quite unable to see any reason for it.

Dr. Lanchester (*contributed*): Although in most respects he found himself in agreement with Dr. Lachmann, there are statements in his paper that he could not let pass without criticism. In a paper which he was to read before the Society on the 12th November he had (Appendix II) for the purpose of instituting a fair comparison between aerofoils of different plan form, suggested a special definition of aspect ratio (symbol $\mathbf{n}$) under which $\mathbf{n} = S^2/a$ where S is the span and a the area of the foil. For the rectangular form this gives the usual value; for other forms the new definition may be taken as giving the aspect ratio of an imaginary aerofoil of rectangular form equivalent to the example under analysis. On this understanding an elliptical aerofoil whose aspect ratio would in the ordinary way be described as 10 would have a value $10 \times 4/\pi = 12.7$. Or the aspect ratio of an aerofoil having a taper ratio $= 0.5$ would be accounted $10 \times 4/3 = 13.3$.

He observed that Dr. Lachmann attributed the vortex theory of sustentation to Prandtl. A quantitative solution of the problem of sustentation founded on the vortex theory will be found in his (Lanchester's) writings published at different times, and is implicitly contained in his "Aerodynamics" (Aerial Flight, Vol. I) published in 1907.* It is admitted that Prandtl was fully acquainted with his work in German as translated by his colleague Prof. Carl Runge in Göttingen (1908) and published by Teubner of Leipzig in 1909. He was introduced to Prandtl by Runge and met him more than once in Göttingen when the translation of his two-volume work was in progress. The author's

* The basis of the theory was given in qualitative form in a paper offered to the Physical Society of London, and actually read in 1904 before the Philosophical Society of Birmingham.

priority in this particular matter has received international recognition, signalised by the award of the Guggenheim gold medal in 1931.

A fair and quite unbiased account of the author's work, and its relation to the work of others in the same direction, is given in "Aerodynamic Theory," Durand, Vol. I (article by R. Giacomelli), pp. 337 *et seq.*

Reply to the Discussion.

Replying to Mr. Walker, the principle of keeping the camber line constant and altering the curvature of the top surface only was not known to him, but it might have some effect. The curves in the paper, referred to by Mr. Walker, were based only on calculation, but a similar method had been tried out in America on a certain Curtiss machine, though it was not done as efficiently as it could have been done. They had put a kind of blister underneath the wing which, of course, altered the camber line and altered the effective angle of incidence, and he was told that the results had been quite satisfactory.

With regard to torsional strength, he fully agreed with Mr. Walker that the important characteristic was torque stiffness. In the weight comparison put forward in part III, section 4 of the paper the shear stress given referred to a wing with skin covering and a concentrated spar (wing A). For wing B (distributed skin) the shear stress in the skin under equivalent conditions would be much less because there was more material to resist the torque and the wing B would therefore be much stiffer than wing A.

Replying to Mr. Gray, that as the available time for his reply was rather limited he would suggest to discuss the question of the transverse flow later with Mr. Gray (See the second discussion.) Meanwhile he would refer Mr. Gray to "Aerodynamic Theory," by Durand, Volume IV, Section II, where the point he wanted to make was very well set out by Prof. Dr. Betz on page 97.

It was not known to him that the value for the rolling criterion had undergone a further reduction. Having expressed his gratitude for Mr. Petter's interesting remarks with regard to the use of tip slots on tapered wings, Dr. Lachmann referred to the use of the stressed skin with very closely spaced stringers. By means of a sketch he illustrated the scheme he had in mind consisting of a combination of corrugated and flat sheet (which was different from that suggested by Mr. Petter), and said that separate panels of this type could be made up rapidly by the aid of a machine riveter.

It appeared that Mr. Williams had misunderstood a remark by Mr. Handley Page. The work described in the paper was not of a purely theoretical character, but was based on very intensive technical research, and, of course, as in any manufacturing concern, the problem of cost had been kept in mind. The principle of making the skin covering up in separate panels had already been introduced into practice by Handley Page, Ltd., and had resulted in a considerable speeding up of production.

Replying to Mr. Radcliffe's remarks concerning the influence of the flap. Tests carried out by Mr. Irving had indicated that a partial span flap did not affect the characteristics of the wing very much. Only the full span flap made things difficult, but when a partial span flap was used the wing behaved more or less as if it had no flap.

Finally, Dr. Lachmann said that he had not quite understood the remainder of the questions, but would reply when they were submitted to him in writing.

At the close of the meeting a hearty vote of thanks was accorded Dr. Lachmann for his valuable paper.

Communicated Replies.

To Mr. Sharman.—Retractile auxiliary wing devices as proposed by Dr. Schmeidler in Germany and Miss MacDonald in this country as similar in their aerodynamic effect to the Fowler wing. It remains to be seen whether they can be made simpler from a structural point of view.

To Mr. Radcliffe.—Mr. Radcliffe's observation that the argument connected with Fig. 12 and its application to a wing fitted with a partial flap required some modification, is correct. The principle itself can be applied also in this case, but it will be found that the critical point—where the margin against stalling becomes a minimum—lies more inboard than in the case of an unflapped wing, namely, just there where the flap ends and the ordinary wing section begins. The wing section at the neighbourhood of this point should be one of a large total angular range, and the maximum twist should be applied here. The distribution of twist and camber along the span will therefore be different for a wing with a partial flap as compared with an ordinary wing, and the suggested method would therefore not offer a solution suitable for both conditions. Although on the basis of this analysis a partial stall should commence just beyond the outboard end of the flap, it is not known whether burbling actually begins here and whether its effect is very detrimental.

To Dr. Roxbee Cox.—The skin thickness in my investigation of the influence on skin weight of taper ratio is assumed to be proportionate to the torque divided by the enclosed area and the shear stress. Loose wording in the original text, which has been corrected, may have caused the impression that skin thickness was taken proportionate to torque only. Although this assumption is in the first place a strength consideration, the torque stiffness will depend on the magnitude of the shear stress f_s. The shear stress to be introduced should be below the value required for pure torsional strength as otherwise waving will cause a torsional deflection greatly in excess of the value calculated on the basis of the Bredt-Batho formula.

For a general investigation like that in my paper, I preferred the assumption of a distributed torque proportionate to the chord and the c_m of the aerofoil section in favour of the somewhat arbitrary assumption of an isolated torque near mid-aileron which forms the basis the Air Ministry required for determining aileron reversal speed. I am well aware of the fact that a local increase of skin gauge over the tip portion of the wing is essential in some cases to deal satisfactorily with this requirement. On large aircraft having wings of fairly high taper ratio, constant skin thickness would cause an unnecessary increase of weight.

In regard to the practical economic aspect ratio, I agree with Dr. Roxbee Cox that a theoretical analysis considering the effect of span on wing weight and on induced drag will lead to surprisingly low values for the economic aspect ratio in view of the high cruising speeds which have lately come into use. Other influences which help to lower the aspect ratio are the relatively low power loadings obtained nowadays with ground-boosted engines, the introduction of V.P. airscrews and the possibility of using a catapult start for initially overloaded long range aircraft.

The negligible effect of aspect ratio on L/D at high cruising speeds is illustrated by the following example: Let us assume a wing loading of 25 lbs./sq. ft., a coefficient of total parasitic drag including profile drag of 0.02 and a cruising speed of 220 m.p.h. Increasing the aspect ratio from 6 to 10 results in improving L/D from 9.05 to 9.4, *i.e.*, by 3.5 per cent., while the corresponding increase of L/D at a cruising speed of 128 m.p.h. would be from 15.3 to 19, *i.e.*, by 24 per cent. It follows, therefore, that unless exceptionally low cruising speeds are admissible—a most impractical assumption nowadays for most military and commercial purposes—it is a better policy to design a fast long range aircraft carrying an appreciable amount of load, with a relatively low aspect ratio of about 5-6 having relatively light wings and thus able to carry more petrol, than an aircraft with a very high aspect ratio which is bound to be heavier due to the inevitable increase of spar weight with span whatever type of construction may be used for the wings.

The general investigations in regard to the superiority of distributed spar flanges over concentrated ones are true in most cases for the outer wings where

usually no big holes are required in the skin. For inner wings concentrated spar flanges, at least on the bottom surface, are usually necessary for tank stowage, etc. In the weight comparison on page 202 concentrated flanges on the bottom surface of the inner wing have been taken into account.

As far as the weight comparison of different forms of wing construction is concerned (Table on p. 202), wings III, IV and V refer to aircraft of approximately the same all-up weight and designed to about the same load factors. The multi-spar wing (III) may be a little handicapped compared with the other wings and may appear relatively heavier than is justified by the effect of the method of construction in view of its lower wing loading and lower taper ratio. Lack of accurate information for all types made a more detailed analysis impossible. However, I have no doubt that even a more refined reduction would not change the picture very materially.

I would not consider the Northrop wing as a multi-spar wing. It is in my opinion a multi-web type with distributed flanges, as the skin is sufficiently thick and well supported to stand high compressive stresses in addition to its duties as a torsion member, while on the multi-spar wing in consideration the skin is only dealing with shear and the material concentrated in the spar flanges is solely used for bending.

I have no doubt that the Northrop construction, from which, after all, most American methods of wing construction based on the principle of distributed flange material emanated, is very light.

To Mr. J. C. Stevenson.—The load factor applied to wings A and B in the numerical analysis of the component weights is 6 and the wing loading 25 lbs./sq. ft. span is 45ft.

A forward limit for the C.G. can be determined by taking into account slip-stream effect on the tail. This effect, however, is not particular to monoplanes fitted with tapered wings.

To Mr. W. E. Gray.—Mr. Gray's question is not very clearly put, but I infer that he assumes that the lift distribution over the wing is not altered by sweep-back. In that case, the torque on the wing is not affected by sweepback, but a couple will be experienced where the outer wings are joined to the fuselage or to the inner wings due to the lift load on the outer wings.

Additional Meeting.

A special meeting was held in the Library of the Society, at 7 Albemarle Street, London, on Thursday, November 26th, for the purpose of continuing the discussion on the paper by Dr. C. V. Lachmann on "Aerodynamic and Structural Features of Tapered Wings," which was read and partially discussed at the meeting on October 8th, 1936. The chair was taken by Mr. H. B. Irving (Fellow).

The Chairman: The meeting was being held in order to discuss further the paper by Dr. Lachmann which was read on October 8th. On that occasion Dr. Lachmann dealt with a very difficult subject in a very comprehensive manner and the only drawback was that there had been very little time left for discussion.

The subject of Dr. Lachmann's paper divided itself into two broad categories, viz., aerodynamics and structural, and he proposed that the aerodynamics side should be discussed first—although the two aspects were very much mixed up—after which the structural side could be taken.

He would like to open the discussion with a few remarks on the aerodynamical side, and the first point he wished to raise was the question of taper and dihedral angle. So far, nobody had raised that point in the discussion. He himself had drawn attention to the difference in stalling properties of the wing which was tapered, by keeping the leading edge straight and sweeping forward the trailing edge and the wing which had a swept-back leading edge and a straight trailing edge. These were the two extreme methods of tapering. If one looked up the

data for parallel wings it would be found that sweep forward gave an anti-dihedral effect, while sweep back gave a dihedral effect, and he felt that that fact must come into consideration with tapered wings. One would therefore expect that a wing tapered the former way, *i.e.*, by giving it an effective forward sweep, would need more geometrical dihedral than a wing tapered the latter way (swept-back), and he asked Dr. Lachmann if designers took that consideration into account in deciding on their dihedral. He felt there was something in all this, because they had a model at the National Physical Laboratory which was tapered in such a way as to give the trailing edge a fair amount of sweep forward, and although it had 5 degrees geometrical dihedral, its effective dihedral—in other words, the rolling moment due to side-slip of that model—was practically nothing.

The other point he wished to mention was the connection between flaps and dihedral. He had heard that with one of the popular types of monoplane, the pilots were warned when coming in and making the approach to land with the flaps down, not to do any side-slipping because if they did the machine had a tendency to " dig in " the forward wing tip. There should, of course, not be any need for side-slipping when the flaps were down but he wondered whether anybody had come across a similar experience. The suggestion was, of course, that the flaps were having some effect on the effective dihedral and he believed there was good reason to believe that lowering the flaps would reduce the effective dihedral in the same way that sweeping forward did.

Dr. LACHMANN: Replying to the first point raised by the Chairman, he said he could confirm that with certain aircraft fitted with tapered wings on which the dihedral was increased in order to get more rolling stability, the effect had been surprisingly small.

With regard to the other point mentioned by the Chairman, he knew that with certain types of aircraft the pilots were warned not to side-slip with the flaps down but he had always thought that was because the gliding angle might become too steep.

Mr. S. H. EVANS (*Member and Associate Fellow*): He believed that the Society were doing a good thing in re-opening the discussion on Dr. Lachmann's paper, because the question of tapered wing characteristics had been one of increasing interest to monoplane designers for some time past, especially in view of the many controversial angles presented by the differing schools of thought. Thus they had high versus moderate taper ratios, swept-back versus swept-forward leading edges, straight tapers versus elliptical tapers, partial span versus full span flaps, not to mention variations in thickness ratio and camber, and several varieties of slot-cum-flap combinations. Designers were especially anxious to know more about the behaviour of tapered wings near the stall; or perhaps he should say their misbehaviour in some cases!

Despite the comprehensive scope of the paper which, indeed, was a valuable contribution to current literature on the subject, it was at once apparent that a really systematic attack at large Reynolds number must be exploited by Government resources before designers could feel confident of their data. For several years past, some of them had been pressing the claims of the tapered wing before the research authorities, because the cantilever monoplane was an obvious design trend even in the heyday of the rectangular biplane. He, for one, attached very little faith in much of the existing low-scale data on tapered wings and he felt that too many plausible deductions were being made regarding burbling phenomena at low scale. Many of those present would recollect the poor showing on that score of thick sections tested in small wind tunnels and the consequent cold water thrown on their development in this country.

Because he believed that the Aeronautical Research Committee might welcome a designer's suggestions on such a research programme, he would like to proffer one or two ideas of his own. He looked upon the basic concept of the elliptical wing as a kind of aerodynamic yardstick, and he felt that the initial work on

tapered wings should be done first of all on the elliptical plan-form before experimenting haphazard with all the manifold varieties of straight tapers now appearing in full-scale practice. The almost total absence of data on elliptical plan-forms struck him as a curious blank spot amidst an ever-increasing forest of unrelated aerofoil data. They needed a thorough-going pressure distribution check on the fundamental plan-form of all their theoretical background, especially at the higher end of the incidence range where existing theory needed a little more empirical buttressing. It was more than probable that some of their official span-loading curves would need revision at high incidence in the light of further analysis from pressure distribution research. This type of *ad hoc* investigation was undoubtedly tedious, but it was of far greater importance to the structural designer than photographing the misbehaviour of wool tufts because the designer wanted quantitative results. Before hunting for an economic taper ratio to meet conflicting aerodynamic and structural criteria, he would suggest a preliminary attack on a related family of elliptic plan-form aerofoils, starting with the circle and stepping up the aspect ratio (or major to minor axis ratio) to as high as 20 perhaps. In this way one simplified the problem by eliminating taper ratio and wing tip effects. From the production angle it might be true that the elliptical plan-form would be more difficult to fabricate, but it seemed equally true that some of the more advanced designs of the past year or so were definitely approaching in that direction. Thus they had Heinkel in Germany, the Supermarine " Spitfire " in this country, and Seversky in the States. Perhaps a practical solution might be a quasi-elliptical form, comprising a straight leading edge combined with an elliptical trailing edge. In any case, aerodynamic refinements were always more costly, but they eventually arrived and became built-in, so to speak.

On the question of taper ratio he could not share the lecturer's advocacy for tapers as high as 4 or 5, however attractive these might appear to the stress engineer. Aerodynamically, he felt convinced that triangular wings (which is what such high tapers closely approached) were every bit as bad as those rectangular planks of the past, despite all the arguments that Dr. Lachmann had so ably presented. Personally, he preferred moderate tapers between 2 and 3, but then again it all depended upon one's definition of the tip chord in the case of elliptical wing tips or quasi-elliptic plan-forms. In order to avoid premature stalling of the tips, Dr. Lachmann invited them to drop their money in the slot, but this looked like rather a weak case for high taper, since he believed that more extensive research would show them how to fashion all the many variables into an optimum combination which would give them the coincident stalling of the theoretically ideal case, *i.e.*, the elliptical plan-form with elliptical lift distribution and constant downwash across the span at all angles. At the same time, he would still use both the lift and the control slot right across the whole wing span to boost the lift of a good wing, rather than to cure the misbehaviour near the apex of a triangular wing. As a matter of fact, he had designed his quasi-elliptic wing with a straight leading edge to take care of a practical front slot installation, so he did not wish to be misunderstood regarding the use of slots; on the contrary, he wished to assure Dr. Lachmann that he was still " full out " for them.

Regarding the structural side of the paper, he would not trespass further because he knew that a number of structural engineers were anxious to ventilate some of their views. However, he would like to thank Dr. Lachmann for the very clear and interesting pictorial summary of metal wing constructions given in Fig. 23 and he looked forward to hearing something more of their various pros and cons. When he had suggested to the Society last year that their next lecture programme ought to explore the subject of tapered wing characteristics he had never expected that both aerodynamic and structural aspects would be covered in one paper by a designer of Dr. Lachmann's technical experience. He well appreciated the tremendous amount of hard labour that must have gone

into its preparation, but perhaps the interest aroused as evidenced by this re-opening of the discussion would be some measure of reward to the lecturer and an inspiration to many of the younger designers.

Dr. LACHMANN: He thought it was beyond the scope of the paper to discuss whether the fundamental assumptions of the Lanchester-Prandtl theory were correct or not. He thought it had been done in the past, but Mr. Evans had suggested that there was a scarcity of full-scale evidence on the question of lift distribution. He knew that Mr. Evans was well conversant with American technical reports and, although at the moment he could not quote the details off-hand, he knew there were several reports which gave full-scale pressure distribution for tapered wings, or a check between calculated and measured lift distributions respectively. A report which had come out recently dealt with the influence of partial flaps.* In this report span load distributions based on pressure distribution tests are compared with lift distributions across the span calculated by the Lotz method and on the basis of a simpler assumption where the flap influence is represented by a horseshoe vortex superimposed on the ordinary lift distribution. Agreement between the calculated distribution and that obtained from the actual pressure plottings is exceedingly good; therefore he did not feel inclined to doubt the basic assumptions of the theory and of methods which are in general use.

Continuing, Dr. Lachmann said the whole problem required to be analysed a little more closely than it had been and he agreed with Mr. Evans that full-scale data were badly required because on his part he did not trust the figures for profile drag as usually presented. At the same time, he believed there was a certain amount of full-scale evidence now available which showed definitely that at full-scale the profile drag of thicker sections was not so high as might be expected from wind tunnel tests. So far as research on these lines was concerned, he agreed with Mr. Evans, but with regard to load distribution and induced drag he personally could not see why that should not be as found by present methods of calculation.

Mr. EVANS: Even with very sharp tapers, especially at the higher end of the incidence range?

Dr. LACHMANN: That was a different story, but, after all, who wanted to use them?

Mr. EVANS: He, personally, thought that 5 : 1 was a very sharp taper; in fact, almost triangular. Even 4 : 1 he felt was a bit " shaky " from the aerodynamic standpoint.

Dr. LACHMANN: He agreed that 5 : 1 might be too sharp and added that he considered 4 : 1 as the practical upper limit.

Mr. EVANS: He usually preferred to keep between 2 and 3 : 1, but with the proviso of a very full elliptical tip, which possibly invalidated the simple idea of taper ratio altogether. While any taper under 2 : 1 he felt was structurally uneconomical, he believed that over 3 : 1 was inviting aerodynamic trouble. He freely admitted, however, it was just a designer's " hunch " and he was prepared to modify these ratios with the advent of further research data.

Dr. LACHMANN: With respect to the tip stalling of tapered wings, this effect was observed in the wind tunnel and also in the air. The use of wool tufts showed there might be certain small qualitative differences, but on the whole he did not think the conditions were very different from what they were conceived to be at the present time. The paper merely purported to put down his own experience and his own conceptions which he had arrived at during the last four or five years. On the question of wing tip slots as a cure for the bad stalling characteristics of highly tapered wings, he would point out that his own firm

* " Span Load Distribution on a Tapered Wing as Affected by Partial-Span Flaps from Tests in the Full-Scale Tunnel." By John F. Parsons. Journal of the Aeronautical Sciences, Vol. 3, No. 5, March, 1936.

were not using them for lateral stability alone, but with the definite intention of obtaining increased lift. Full-scale evidence had well confirmed the theoretical prediction and he was glad to have Mr. Petters confirmation in this respect.

Mr. EVANS: Did Dr. Lachmann think it possible to design a tapered wing without slots which would have really satisfactory control and stalling characteristics, at least as good, if not better than had been obtained in the past from the rectangular wing? He, personally, believed that the quasi-elliptic plan-form was the first requirement. By that he meant more particularly the plan-form over the aileron span because he had always contended that one could not expect smooth flow from lower to upper surface of the wing over the end of a rectangular plank, neither could one cajole it over the apex of a triangle.

Dr. LACHMANN: He thought that the method suggested in the paper, a twisted wing with increased tip camber, would be a possible solution, due to the increased angular range of the tip sections compared with the root sections. Most of the trapezoidal wings now in use had smoothly rounded off tips.

The CHAIRMAN: He was not a member of the Aeronautical Research Committee, but there were members present and he was certain they would welcome the remarks which Mr. Evans had made. They were only too pleased to meet designers who had constructive ideas on research, because occasionally when they tried to get ideas from designers as to what the course of experiment should be they did not have very much success.

On the question of carrying out experiments at large Reynolds numbers, he agreed that this was advisable, especially in the region of the stall. So far as the region below the stall was concerned, it was surely reassuring to get lift-incidence curves from the compressed air tunnel, in which, as the Reynolds number was increased from low to very high values the part of the curve below the stall remained the same. That held for all thicknesses up to 20 or 25 per cent., and they would agree that it was reassuring as regards distribution of loading obtained from the ordinary model test.

Dr. LACHMANN: In the calculations of load distribution with tapered wings or, indeed, any shape of wing, the only experimental item used in the calculations was the slope of the lift curve, which was assumed constant in the theory. While it was true that constant slope did not hold at the higher incidences and, therefore, the theory might be a bit uncertain, he did not think there was any doubt about the lower incidences. Besides there were graphical methods available, for example the method of Tani, which allowed calculating the lift distribution for a non-linear slope of the lift curve.

Mr. EVANS: Is it true that with trapezoidal plan-forms with high tapers approaching the triangular, some of the experimental work showed high peak loadings at the tip, especially at high incidence?

Dr. LACHMANN: He agreed and pointed out that the theoretical calculations definitely indicated this, as reference to Fig. 7 would confirm. But he wished to repeat quite distinctly, in view of Mr. Stanley Evans' remarks, that he was not an advocate of triangular plan-forms. In fact, he had not "advocated" any particular taper ratio, but had only drawn attention to the structural and aerodynamic consequences resulting from variations of taper ratio. As for the elliptical plan-form, he failed to see what special advantages Mr. Evans was expecting. With taper ratios between 2 and 3 the induced drag was practically the same as for an elliptical wing of the same aspect ratio; in any case, the difference was only of the order of one or two per cent. Moreover, in a modern high-speed machine, induced drag was relatively unimportant, since at top speed or high cruising speed it was very small compared with skin friction and parasitic drag.

Dr. N. A. V. PIERCY (*Fellow*): In the first two sections of the paper the author gave alternative methods of calculating flange weights, and although some designers might favour the first method set out, he believed that further research

would indicate a mean course. The research needed first was to establish the variation of form drag with thickness ratio and this matter had become urgent both in the present connection and in relation to performance prediction. Meanwhile, he did not see how it was possible to ignore the paper given by Fage, Falkner and Walker (R. and M. 1241) in 1929, and he had prepared a slide based on that paper. If the National Physical Laboratory regarded that paper as superseded, he wished they would say so, because it appeared to be a careful piece of work of lasting value.

His next point, said Dr. Piercy, was that he thought analysis of tapered and twisted wings was based far too much on the present methods of aerofoil theory. With regard to induced drag and other effects of that kind (dk_L/da, etc.), the theory was very satisfying, but when it came to estimations of the wind direction towards the wing tip, then he thought it should be realised that the theory, as used, was hypothetical and certainly could not, and did not, accord with facts. The elliptic wing, for example, was a mathematical figment; even from the mathematical point of view the flow supposed round its ends could not be a physical fact, while countless experiments had shown vortex knuckles to exist near the wings, and these strong vortices meant that an appropriate part of the lift was uniform. In his own experiments published by the Society some years ago on rectangular wings, the proportion of uniform lift was between 50 and 80 per cent., and it follows that the flow around the tips was quite different from that at present calculable by the methods of aerofoil theory. Glauert's R. and M. 889 included a tapered aerofoil. There were two conclusions. The first was that the analysis of tapered wings and twisted wings erred on the wrong side for safety because it dealt with only part of the lift at best. The second conclusion was that it would soon be necessary to take into account the flow that actually existed and cease to assume that fluid velocity could be infinitely great and fluid pressures infinitely negative. To a certain extent, therefore, he was in agreement with Mr. Evans' remarks.

Mention was also made by Dr. Lachmann of the influence of twist, and he agreed that, as stated in the paper, twist tended to become too large to be effective. Had Dr. Lachmann discovered any consequent difficulty with the downgust case of loading?

The next point was in connection with the important Fig. 14*a* of the paper referring to static stability, and he would like to know whether any startling effects had been discovered with regard to the stability derivatives M_q or M_w. Had Dr. Lachmann extended his experiments in this way?

Dr. LACHMANN: He had not. The curves in Fig. 14*a* referred to a machine which was flying now.

Dr. PIERCY: And the longitudinal stability has not been analysed?

Dr. LACHMANN: No. It is what they expected it to be.

Dr. PIERCY: The curves were so striking that one almost expected some difference from usual results round the stall in M_q.

The CHAIRMAN: The M_q due to the wings was very largely contributed by the tail. For an ordinary parallel wing machine, which was the only way this had been done, the M_q was very small.

Dr. PIERCY: Exceptionally large static moments from other parts were given in the figure.

Dr. LACHMANN: These results were based on wind tunnel tests for a certain C.G. position. The C.G. limit, where stability becomes neutral, was estimated from these results and flight observations confirmed the prediction.

Dr. PIERCY: There was no trouble with the short oscillation at the stall?

Dr. LACHMANN: No. At least there was no report from the pilot to that effect.

Dr. PIERCY: He did not find flying steadily at the stall a bit difficult?

Dr. LACHMANN: No, not to my knowledge.

Dr. PIERCY: The Society might expect a statement from him regarding the further work that was being done at Queen Mary College under the auspices of the Government of India by Mr. Nazir, whose original experiments had been causing so much controversy. Mr. Nazir had been experimenting on the lift of ailerons, of course on a small scale, and he had been able to postpone the tip stall by about 5 degrees and get unabated rolling moments beyond 20 degrees, which, personally, he thought was quite good. Mr. Nazir's experiments had been most striking with the cut slot in association with a trailing edge aerofoil of the kind that had been used by Junkers for slow landing for some years and some of the results obtained might seem almost fantastic. It was hoped that he would be equally successful with regard to over-all maximum lift coefficients. The work being done he believed would make the flap and similar devices more safe than they were at present. He agreed with Dr. Lachmann that difficulties with the tapered wing were only there to be overcome.

Dr. LACHMANN: Could Dr. Piercy say what the cut looked like in the case of the experiments of Mr. Nazir?

Dr. PIERCY: It was a fixed but sealable cut through the wing behind the back spar which could be used in conjunction with the flap or a Junkers aerofoil.

(Dr. Piercy wishes to make it clear that he does not attack Prandtl's aerofoil theory, but only application of the ideally simplified analytical methods now in common use to connections not envisaged by Prandtl—as for example in assuming the flow round the ends of the elliptic wing of mathematical theory to be a physical fact.)

Mr. P. P. NAZIR (Queen Mary College): With reference to the author's remarks as to tip stall with very sharply tapered wings, he said he thought there was every possibility of being able to change the sharp stall to a moderately intermediate stall. This would make the stalling aspect of the tapered wing almost equal to that of the rectangular wing. Work had been done on this and full results would be published shortly, so that he must anticipate them, but the work in question showed the effect of different types of stalls occurring upon wings. There were two types of stalls, viz., the leading edge stall, and the trailing edge stall, and it had been shown that advantages were to be obtained by improving the trailing edge stall.

Mr. R. P. ALSTON: With reference to tip stalling, he said there were cases where, even though the tips were stalled, the lateral stability was not bad and it was not a *sine qua non* that because tip stalling was avoided the lateral stability would be good, and if there was tip stalling the lateral stability would be bad. He had a case in point where the lateral stability of the machine was improved by giving sharp leading edges to the tips of the wings in such a way that a definite stall was produced. He thought the reason for that was that the wing-dropping characteristics at the stall were very largely dependent on the type of stall. It seemed that a little too much attention was being paid to lateral stability at the stall as deduced from calculations of local incidence and even wool tuft observations.

Another point which seemed germane to this was the question mentioned by the Chairman of the effect of high taper on lateral stability in normal flight where there was no question of stalling. He believed there was a certain amount of evidence that for very highly tapered wings the stability term L_v was reduced as compared with medium taper and rectangular wings, and it was rather distressing to hear from Dr. Lachmann that in one case the stability was not much improved by an increase of the dihedral; perhaps a little more attention to the stability characteristics of tapered wings in normal flight might be worth while, rather than paying so much attention to the stall, since in landing, a machine with high drag flaps was only at a high incidence near the stall for a very short time at the last stage of flattening out when very close to the ground. A certain machine with highly tapered wings of which he had experience had vicious stalling

characteristics in free air, but it was stable close to the ground when landing. It seemed, therefore, that interest in tip stalling and lateral stability should be directed towards preserving adequate lateral stability when gliding and landing with flaps down, and towards the avoidance of incipient spins in aerobatics and manœuvres at high incidence with flaps up. He felt that the two things should be treated separately.

Dr. LACHMANN: He mentioned Matteoli's scheme and also referred to the flat-topped though completely stalled lift curve obtainable with interceptors.

He did not suggest for one moment that this would be an advisable scheme for stabilising a machine. He felt there could be no doubt that if the tips were not stalled, it was better.

In answer to the Chairman, Dr. Lachmann said he understood the Matteoli scheme was to put a little streamline wire in front of the leading edge. This resulted in a certain loss of lift, but produced a flat-topped lift curve.

With regard to stability in normal flight, he felt he had been misunderstood. When he mentioned at the beginning of the evening that decreasing the dihedral did not have such a big effect as was anticipated, he did not mean to suggest that the machine was pronouncedly unstable. Everybody knew that the degree of spiral instability did not depend solely on the dihedral, but also on the size of fin and rudder and the two quantities had to be matched. The reduced value of L_v for a tapered wing stood not in the way to obtaining similar characteristics in regard to spiral stability as for aircraft fitted with rectangular wings provided this effect was properly considered in the design.

Mr. W. E. GRAY: He would refer to one or two points already raised in the discussion. Mr. Evans had asked for some rational way of defining taper. He did not know whether taking the centre of area met the point, but it was perhaps at least rational. In a parallel wing the figure would be 0.5 and a triangular wing 0.333 of the semi-span.

Mr. EVANS: He had suggested the block coefficient which he thought was more self-explanatory, because it took care of any curvature of the leading edge or the trailing edge. However, he did not think it was very important.

Mr. GRAY: He thought that the centre of area was truer. Continuing, he commented on the remark of the Chairman with regard to stability in a sideslip with flaps. The Chairman had mentioned that point to him a day or two ago and he had suggested to Mr. Irving that it might be due to the tail getting out of the increased downwash behind the flap. He had done one or two small tunnel tests yesterday (at very low Reynolds number) to see if that were so, and apparently there was a very sharp change over in the downwash behind the end of the flap. It would depend on the span of the flap, but the tail would probably be getting largely outside the flap downwash in a sideslip of 20 deg.

Explaining the point further with the aid of a sketch, he said that there was a change over of something like 10 deg. The downwash behind the flap was more than 10 deg. greater than it was just outboard of the flap and he suggested that this sudden change might be the explanation—as the tail came out of the flap downwash there was an altered pitching moment, raising the tail. He did not quite understand what Dr. Lachmann meant when he spoke of having the gliding angle too steep.

Note (communicated).—A further brief test has been made to find whether the suddenness of the change in downwash can be avoided by ending the flap gradually instead of abruptly. In place of a half-span flap of 15 per cent. c. width, one was fitted over 60 per cent of the span and having its centre half parallel and the remainder tapered straight to zero at the tips; the sudden change in downwash still persisted at about 50 per cent. of the semi-span, *i.e.*, inboard of the flap end. A flap was next fitted over the whole span and having a uniform taper from 15 per cent. c. at the mid-span to zero at the tip; this had the effect of intensifying the tip vortex greatly and of eliminating the previous sudden change of downwash entirely. The Reynolds number, as before, was very low;

the plan form was as a Miles Hawk—slightly tapered, and all flaps were split ones at 60 deg.

Dr. LACHMANN: With a very steep gliding angle obtained with flaps down, there was no need to sideslip. If there was sideslipping the gliding angle became even steeper, but one did not want to come down like a brick. He felt, however, that the explanation given by the sketch which Mr. Gray had drawn was probably correct.

Mr. GRAY: With reference to Mr. Alston's remarks, he said he thought that the case of lateral stability with flaps down as one approached in landing should also be kept in mind. When the machine was relatively near the ground they wanted the flaps down.

Mr. ALSTON: With a reasonably high drag the machine should be miles away from a stall right until the very last moment.

Mr. GRAY: In wind tunnel work he thought it was important to try to get away from merely the flow on the surface, because that was not always anything like a sure guide. There might be local flow on the surface which was quite different from the flow at a distance above the surface and it was necessary to know what was happening above the surface.

The CHAIRMAN: He also wanted to enter a plea that the wool tuft did not tell the whole story, but when dealing with a whole family of wings and it was desired to cover the ground in a reasonable time, it was necessary to restrict oneself somewhere.

Mr. GRAY then showed a number of lantern slides. The first showed the airflow over a high-lift wing extending right across the tunnel at 20 deg. yaw. The section was one used by Messrs. Bryant and Williams in 1925 for two-dimensional flow tests and had a flat under-surface and T/C ratio of about 19 per cent.; the chord was 10 cm., the incidence 5 deg., and the speed between 3 and 4 f.p.s. A trail of titanium tetrachloride smoke showed the flow in plan view, and the smoke passed at a distance of approximately 5 per cent. C. from the upper surface at the 10 per cent. chord point from the L.E. The smoke showed how the flow was bent suddenly towards the up-wind end of the wing when in the region of the leading edge and how the curvature was reversed as it passed the remainder of the wing until finally its path was approximately parallel to its original path, but laterally displaced from it. The flow at 25 f.p.s. was very similar but too difficult to photograph with smoke. The flow below the wing was bent in the opposite way, so that the air below the wing was displaced one way and air above the wing the other way and remained displaced after passing the wing.

He said that Mr. Lock, of the N.P.L., had suggested to him that the probable limiting value of any spanwise component of flow would be, he thought, the spanwise component of velocity of the flow before it met the wing; Mr. Gray said that he had therefore done some tests to find out if this were so, and had measured the velocities and the directions of the flow at one or two points by means of the hot wire method. While the readings taken in the retarded region near the T.E. had shown that the spanwise component of velocity there was somewhat less than the original spanwise component, and very close to the surface was very considerably less, the only reading taken so far in the forward region gave a reading of just over 10 deg. bending, whereas if Mr. Lock was correct there should only be just over 8 deg. bend; he did not think that his possible error was as much as that, but would have to try to check it more carefully. (*Note (communicated later)*.—Check tests have since been made and results obtained agreeing to within 0.6 of a degree, instead of the 2-degree discrepancy; this is probably well within the limit of the experimental error. Mr. Gray now agrees that Mr. Lock's view expressed above must be correct, provided the pressures along the span are uniform and the chord parallel, for in these circumstances the accelerations of the air can only be in a chordwise direction and therefore cannot alter the original spanwise component of the flow; but,

of course, if a finite parallel wing begins to stall sooner at the down-wind end owing to an accumulation of dead air, or in a tapered wing, this consideration no longer holds good.)

A further slide showed the flow at 3 f.p.s. over a tapered half wing when partly stalled. The taper was 2.5 to 1 and the L.E. swept forward at 5 deg.; a 20 per cent. split flap at 45 deg. was fitted over the inner half of the wing, and titanium smoke showed the trailing tip vortex and also another vortex of opposite rotation in the stalled region above the trailing edge and flowing towards the root. Mr. Gray said that he had not yet formed an opinion as to the significance of this vortex, as he had only discovered it the day before. (*Note (communicated)*.—This has now been found to be merely the " reversed " flow rotating in the stalled region and being drawn along the span under the influence of the swept T.E. and the flap.)

In another slide the flap had been removed and this second vortex was less marked, but the dead air was still carried from tip to root, and did not move off down-stream over the outer half of the wing at all.

Two further slides were shown, the T.E. being swept back 10 deg. The dead air was now seen to be leaving the tip part of the wing indiscriminately, and with flap off the vortex in the stalled region had been observed to be carrying the dead air towards the tip. With the T.E. normal to the wind the flap drew dead air from the outer half of the wing into its own wake and the T.E. spiral or vortex could be seen, he said.

Dr. LACHMANN said that he had carried out some tunnel tests on a yawed wing to satisfy himself as to the bending of the flow, but his results did not seem to agree with Mr. Gray's first slide.

Mr. GRAY replied that he was sorry, but *his* evidence was photographic! (*Note*.—On comparing results afterwards it was found that there was substantial agreement.)

Dr. LACHMANN: He congratulated Mr. Gray on the very fine work he was doing, the more so as he was a free-lance research worker. He believed Mr. Gray was on the right lines now when exploring the flow at the tips of a yawed wing and its influence on the rest of the wing. He had looked up some literature on this point and had found that a certain amount of work had been done by Blenk in Germany—this was theoretical and did not deal with the effects of stalling—and also by Del Proposto, whose dissertation was published in Aachen in 1933.*

Del Proposto's investigations deal systematically with the behaviour of yawed rectangular aerofoils. In order to explain the difference in sign between theoretically calculated and actually measured rolling moments of yawed aerofoils he investigated the effect of the tips by pressure plotting and found that very pronounced low pressure regions were caused by the flow impinging on aerofoil sections with a cut-off nose. However, this effect was found to be of a secondary nature on the strength of experiments where the tips were modified so that the contour was parallel to the direction of the wind.

* " Über das Verhalten von Tragflächen bei Seitenwind." By Sergio Del Proposto.

To explain the still existing very considerable difference between experiment and theory, Del Proposto put forward the following hypothesis: The pressure gradient normal to the direction of the flow causes the boundary layer to flow from the upstream wing tip towards the downstream wing tip, thus preventing the forward wing tip from stalling and accelerating stalling of the rear tip. Thus strong moments result which are opposite in sign to the theoretically calculated moments.

As far as the bending of the flow in the centre portion of the wing was concerned, it rather appeared to him that Mr. Gray found his own theory not quite satisfactory and he seemed to have given up the idea of the theory that the bending of the flow was due to transverse pressure effects.

Mr. GRAY replied that he had not. There was a bending first one way and then the other, and he still thought that the real causes were the cross-wind pressure gradients.

Dr. LACHMANN said he thought that Lock's theory was satisfactory, because if one had a parallel wing and the resultant flow was not normal to the leading edge, it could be resolved into a component normal to the span, and a component which was span-wise. Going along the wing section it would be found there was a high local velocity and, as one approached the trailing edge, the component in the direction normal to the span became less and less and therefore the effect of the span-wise component became more pronounced and the result was a bending of the flow.

Mr. GRAY: Dr. Lachmann had not allowed for bending at the leading edge.

He remarked that he was inclined to think that the two points of view were just different ways of looking at the matter. Mr. Lock's way was perhaps more theoretical. He himself wanted to know why the air did not follow a straight path; he believed it was because of the cross-wind pressure variations.

Dr. LACHMANN: Perhaps it came to the same thing.

The CHAIRMAN: The discussion so far had been on the aerodynamical side and no doubt the structural people wanted to say something. Before going to the structural aspect, however, he would like to ask whether Professor Hill had anything to say.

Professor G. T. R. HILL: He would like to draw a picture of the stabilising effect of sweepback as compared with that produced by the dihedral.

If a wing was swept back there was an ordinary increase in rolling stability and that could be regarded as separate from lateral stability as a whole. It could not be said that any amount of sweepback was equivalent to any given amount of dihedral, because the stabilising effect of sweepback depended very much on incidence. In fact, at the angle of no lift, there was practically no stabilising effect, and the effect increased more or less uniformly with incidence, up to the stalling angle, whereas with dihedral angle that statement was not true. There was no equivalent between sweepback and dihedral. The two things had to be taken separately. It all went to show that flying was becoming very complicated and so much was happening in these days and it seemed that the work which Mr. Gray and others were doing would probably bring them into a new region of knowledge. At the present moment they were in rather an unknown region, and it was to be hoped that those who had the facilities for this kind of work would continue their investigations.

Continuing, Professor Hill said he would like at this point to end his speech as a private individual and make a few comments as a member of the Aeronautical Research Committee. He wanted to say officially that there was no feeling in the mind of any single member of that Committee that all knowledge and capacity was concentrated at any of the official establishments. They did definitely welcome such contributions to knowledge as had been provided, if he might select one example, by Mr. Gray that evening. It was quite obvious, of course, that the more minds there were at work to help to solve this problem the quicker they would arrive at a solution. Before sitting down, Professor Hill said he

would like to thank Dr. Lachmann for providing, as it were, a groundwork on which it had been possible to have the present discussion which had been to him extremely interesting.

Mr. HENRY DAVIES: A great deal had been said by the author on the kindred subjects of taper ratio, skin weight and torsional stiffness, but he found it difficult to accept some of the conclusions set out in the paper.

There appeared a statement that the skin had been assumed to be thinned down along the span, proportionate to decrease in torque. This was stated to agree with current structural practice. Later appeared a statement that the design criterion for cantilever wings, which determined flutter speed and critical reversal speed, was the torque stiffness. He concurred heartily in the latter statement, especially in the case of monoplanes with a very high terminal nose dive speed and a probable top speed at high altitude of 300 miles per hour or more. Actually, however, in order to achieve this torque stiffness, the gauge of the skin towards the tip became exceedingly important. It might be difficult or impossible to thin down the skin over the outer portion of the wing, as Dr. Lachmann had suggested, and this was notably the case for wings with high taper ratio (4 : 1 or 5 : 1) favoured by the author.

Mr. Davies asked the meeting to consider the case of a wing with a root "t/c" ratio of 18 per cent., a tip "t/c" ratio of 9 per cent. and a taper ratio of 4 : 1, and to assume the torque to be taken by a continuous box section with a chordwise dimension proportional to the wing chord. The tip chord was one quarter of the root chord. The tip depth was one-eighth of the root depth; the tip enclosed area was 1/32nd of the root enclosed area. In other words, the outer portion of the wing was astonishingly flexible in torsion and it might be necessary actually to increase the skin gauge in proceeding outboard along the span. In order to achieve the desired torque stiffness—both from the point of view of flutter and critical reversal speed of ailerons—he believed two things to be necessary: (1) Avoid excessive taper ratios exceeding (say) 2.5 : 1; (2) prolong the gauge of the spar box selected as suitable for the inner portion of the wing, some distance further outboard than would be necessary for dealing with torque stresses only.

Continuing, Mr. Davies said he had preferred not to give a mathematical analysis, but the conclusions he had given were based on experience with this type of construction. They applied in particular to a monoplane with a top speed in the neighbourhood of 300 m.p.h., and perhaps to a lesser extent to slower aircraft.

Fig. 3 of the paper gave an idea of the economy in structure weight due to taper ratio. The result was what one would expect. If the "t/c" ratio were kept constant, then the wing with a large taper ratio would automatically have a large spar depth at the root. Such weight saving as was possible seemed to be due almost entirely to this spar depth at the root and not to the slight reduction in root bending moment obtainable with a high taper ratio. Incidentally, a pronounced taper in the spar webs had quite a useful effect in reducing the shear stress in the web in normal flying cases. Altogether, then, from the bending point of view the wing with the high taper ratio offered advantages, but these were offset by the torsional stiffness requirements for wing flutter and critical reversal speed. Therefore, a compromise was necessary depending among other things on the speed of the aircraft.

Aerodynamically, a very high taper ratio almost necessitated the use of a wing tip slot in order to preserve damping in roll, the only alternative being an excessively large wing twist with consequent increase in wing drag at top speed. The additional lift afforded by a wing tip slot to a wing flapped over its inner portion—as shown in the paper—was very impressive. Current design of monoplane wings tended to a moderate taper ratio (2 or 2.5 : 1) combined with a moderate wing twist (3 to 4 deg.) without wing tip slots. The paper conveyed

the impression that this amount of washout was inadequate to secure proper damping in roll.

He called attention to the statement that the design stresses in flanges of extruded material are considerably higher than those obtainable with usual combinations of skin and stringers. That was true, but it need not be the case. It was possible to provide, either by a combination of skin and stringers or of skin and corrugations, a surface which had nearly as good a weight-strength ratio in compression, as a concentrated flange, and since all additional torque bracing and fabric covering were dispensed with, he did not doubt for a moment that a shell stressed wing, of correct design, was the ideal solution for a monoplane wing. He was glad to note that on the concluding page of the paper the author was of the same opinion.

Certain points, however, required to be noted. The spar webs—especially the front spar web in such cases as C.P.F. and landing—were subject to fairly heavy shear and if economically designed were certain to be waved. These tension waves demanded a spar boom which was capable of withstanding local bending stresses in addition to end load. Further, local bending in a plane normal to the web, might possibly be induced by tension fields in the top and bottom skin. For this reason, he did not think it was ever desirable to take *all* the bending load through the top and bottom skin. A compromise was preferable. Spar booms should take a certain proportion of the end load and they should have adequate local bending strength in the plane of the web. The remainder of the end loads should be taken through a suitably reinforced skin. As a suitable reinforcing, corrugations had obviously much to recommend them since they contributed both to the bending and torsional strength of the wing. A fairly deep corrugation in the high grade alloy, with stabilising ribs at close pitch, seemed a good solution of the general problem.

The efficiency of the skin under end load was obviously influenced by considerations of shear. The strain energy stored in shearing the skin tended to make those parts of the skin, and its reinforcement, which were some distance from the spar booms, rather less effective under end load than those parts that were quite close to the booms. This effect, however, was not really very great unless the spars were very wide apart and the gauge of the skin rather low. Another effect which needed to be dealt with was the actual compressive strength of skin (or skin and corrugation) when carrying a high shear stress, *e.g.*, the skin just aft of the front spar in Fig. 23.

Dr. LACHMANN: Replying on the question of the skin thickness towards the tips, he said he would like to point out that the formula he had developed was of a general nature in order to get some idea of the skin weight ratio, especially in the case of larger aircraft, where the criterion of aileron reversal speed was less exacting than for small aircraft of high diving speed. He agreed with Mr. Davies that the enclosed area was reduced if the wing was tapered, but at the same time the torque was reduced because it was proportional to the chord. The reduction of torque occurred indeed at a slower rate than the reduction of enclosed area, but this effect was properly represented in the formula. He also agreed with Mr. Davies in regard to the necessity of shift web flanges in order to withstand local bending stresses. It was therefore practically not possible to take all the bending load through top and bottom skin.

Mr. DAVIES: The torque was not proportional to the chord in the case of a concentrated aileron load.

Dr. LACHMANN: That depended on the assumption. If the assumption was made on the basis of the Air Ministry requirements for aileron reversal speed, he agreed with Mr. Davies, but in his formula he had thought it better to take the torque as proportional to the chord. He was not dealing with aileron reversal speed because it would be more difficult to have a general expression on the assumption of an isolated torque. He did not think Mr. Davies objected in general to the theoretical conceptions on which the formula was based. As to

the numerical values, he had checked them up for a certain wing designed to his firm's normal stress requirements and the calculated weight came out within 5 per cent., which showed that the assumption was not so bad.

In regard to combined compression and shear stress in the skin, he had suggested in the paper that some research be done on this line. At the moment we were a little in the dark on this point except that he had seen one curve published, which gave the function between shear and compression stress. He did not know to what extent the curve in question was representative but it was, according to his knowledge, the only published information in existence.

Mr. E. E. Blount (Scottish Aircraft): He would like to contribute something on this question of decreasing the thickness of the skin towards the tip. In actual experience he had generally found that the minimum skin which was considered advisable in the U.S.A., to use for practical considerations, was more than adequate to take care of the torque, so that it was usually a question of constant skin thickness from root to tip and having excess thickness for structural purposes. On the question of the skin taking compression and shear together, all the experiments carried out in America in that connection had indicated that the skin would take very little compression, and that in a case such as had just been mentioned where there was theoretically compression in the skin in addition to shear, the skin would be so thin in most practical cases that it would actually be taking that shear as a tension field. In the case of pure torque, the shear would produce a tension field at an angle of approximately 45° to the torque axis, and in the case of additional compression on the skin, the effect would be merely to increase the angle so that the tension wrinkles were more nearly parallel to the ribs.

Continuing, Mr. Blount referred to the variation in stress from the region adjoining shear webs to the region in the middle of the wing some distance from either the front or rear shear webs. A good many experiments, he said, had been made in America to determine this variation of stress and he had found it to be very small. Usually, the normal curvature of the upper surface of the wing would make the material in the middle of the wing a sufficiently greater distance from the neutral axis to give it more stress than the material adjacent to the shear webs, so that although there was some reduction, it was not enough to compensate for the curvature of the wing. He was rather dubious about the possibility of carrying as much stress in a combination of skin and stiffeners as was permissible in extruded sections used as spar flanges, where the material was stabilized in both directions.

Mr. Davies: He could not agree that it was impossible to get a combination of the two stresses. He could not refer in detail to tests which he had carried out, but they certainly showed that it was possible to make a fairly thick skin with stringers placed fairly close together and with stabilising ribs at close pitch. With such an arrangement it was possible to make the skin astonishingly effective in pure compression.

Dr. Lachmann: Even with the most efficient skin-stringer combination one could not achieve the same compression stress as with extended flanges.

Mr. Davies: The figure was always a little fictitious because of local bending effects due to tension waves from the web, and for that reason it was not the practice to work the spar booms, with normal construction, up to the principal stress. With spar booms of extruded metal like *R*56, they should take something like 20 tons in pure compression, but in most constructions of this type it would be found that they could not work up to that, but only to about 15 tons. It might be a little higher but he could assure them that if they placed the stringers close together and had a fairly thick skin, and also if the stringers were stabilised at fairly close intervals, they would get a combination which would work not quite up to the same stress but to something approaching it.

Dr. Piercy: Is a 22 gauge alloy meant?

Mr. Davies: No. Something thicker than that.

Mr. BLOUNT: His experience was that in small ships where the ribs could be put close together, it was possible to approach closely to the stresses obtainable in extruded sections, especially where the loads were high and the wings so thin that a great deal of material was required. In such cases they could afford to have stringers close together and a thick skin, but when larger aeroplanes were under consideration the economy of material was very important. In a large ship the use of ribs close together would be uneconomic.

Dr. LACHMANN: It all depended on what was called a large ship. Would Mr. Blount call a 12 ton ship a large one?

Mr. BLOUNT: He would consider 12 tons about medium size.

Dr. LACHMANN: He had found in that size that it was possible to have sufficiently heavy gauges in the corrugated section so that very good stresses were obtained, practically equivalent to the yield point stress, over a large portion of the wing.

Dr. PIERCY: Could 16 gauge be obtained at 12 tons?

Dr. LACHMANN: On the inner wing constructed with distributed flanges it was possible to get 16 or 18 gauge.

Referring to the suggestion by Mr. Blount that there should be constant thickness of skin from root to tip, he said surely that was only possible for small aircraft having wings with concentrated spar flanges. According to his experience with machines of about 10 tons all-up weight, they had 20 to 22 gauge skin at the root and that was cut down to 26 gauge at the tip except for certain local reinforcements to meet the aileron reversal speed case. Retaining 20 or 22 gauge throughout the skin from inner end to the tips would make the wings too heavy and much stiffer than necessary.

With regard to Mr. Blount's remarks on compression stress under the influence of shear stress, he could only imagine that reference was made to the panel type of construction which he did not consider as being as efficient as a really stressed skin panel, viz., a panel with fairly wide stringer spacing. Obviously, in such a case there was only a very small effective width.

With the other type, however, *i.e.*, with very close stringer spacing or with a combination of flat and corrugated skin a very efficient panel was obtained, because the effective width of the flat skin was continuous. Here the flat skin took quite a large compressive stress and therefore the problem of combined compression and shear stress became quite important. In the other case there was no such problem. He believed that American practice differed in this respect, for example, Martin made the flat skin very thin so that it only took shear. Douglas went for a heavier gauge flat skin. He personally favoured for still heavier gauge than was customary in America. The actual skin should not only be a cover taking a portion of the shear stress but should also take a very high compressive stress.

Mr. A. E. RUSSELL (*Associate Fellow*): Mr. Davies had raised two points which he himself had intended to mention. There was one matter which had not been amplified, viz., that the torsion loads which mattered were those due to the wing twist, and as that was greatest at the tip the torsion loads that mattered were highest at the tip and zero at the root. Therefore, it was more important to increase the skin thickness at the tip than at the root. Concerning the comparison between concentrated spars and reinforced skin, he had made several test spars with extruded flanges using 22 S.T. and he had never yet failed to achieve a stress less than 24 tons per square inch, a higher figure than Dr. Lachmann has used in his comparison. It was very much more difficult to vary the strength of reinforced skin along the span than concentrated spars. With the latter it was possible to approach uniform stress distribution, whereas it seemed that the former could only develop its maximum capabilities at isolated points. At other places either the whole of the available chord was not used, or if used, not developing the maximum stress.

Dr. LACHMANN: He did not quite agree with Mr. Russell. It was true that in the case of the extruded spar it was easier to vary the section, but generally speaking he thought he had been misunderstood on the point. He did not wish to convey the impression that he thought that reinforced skin was the only solution infinitely superior to the construction using concentrated spar flanges. Obviously there was room for both. Indeed, the point he had wished to bring out in his comparison in the paper was that there could not really be a great deal of difference in regard to structure weight for any possible technical solution. For small aircraft he felt there was very little to choose between the fully stressed skin and the usual box with extruded flanges. On large machines he believed that the distributed flange system definitely scored to the order of about 3 per cent. on the all-up weight.

Mr. BLOUNT: He agreed and said he thought it possible to design a very efficient wing with extruded flanges for an aeroplane weighing as little as 12,000 lbs.

Further reply to Messrs. Davies and Russell.—The investigations in regard to torsional deflection of a tapered wing have been extended to cover the case of an isolated torque acting at mid-aileron span (see Appendix).

These investigations confirm in a way the views expressed by Messrs. Davies and Russell that for aircraft of very high diving speeds the torque stiffness to ensure a sufficiently high aileron reversal speed will become the decisive design criterion overriding strength requirements, at least as far as the major portion of the outer wings is concerned. For relatively small and fast aircraft there will therefore be only a limited scope for practical variation of skin thickness along the span.

On medium size and large aircraft, however, which need not satisfy terminal velocity conditions, it will be found on closer examination that for the inner portion of the wing the distributed torque will form the decisive design criterion whilst the outer wing will be affected by the stiffness requirements of aileron reversal speed, although very often skin thickness based on strength considerations alone, with a relatively low shear stress fixed to avoid excessive waving, will be sufficient to deal with the less exacting aileron reversal speed criterion of large aircraft.

The meeting then closed.

THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS.

SEVENTY-SECOND ANNUAL REPORT OF THE COUNCIL.

1936-1937.

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Advisory Council of the Science Museum: Lord Sempill.

Air League of the British Empire: Mr. W. O. Manning and Mr. Griffith Brewer

Association of Special Libraries and Information Bureaux: Mr. J. E. Hodgson (Honorary Librarian).

British Corporation Register of Shipping and Aircraft, Aviation Committee: Lord Sempill.

British Gliding Association: Council: Mr. W. O. Manning.
Technical Committee: Captain J. L. Pritchard, Professor F. T. Hill.

British Standards Institution, Aircraft Committee: Major R. H. Mayo and Dr. H. C. Watts.

British Standards Institution, Committee on Symbols and Abbreviations Used in Engineering: Major A. R. Low.

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Lloyds Aviation Committee: Lieut.-Colonel J. T. C. Moore-Brabazon.

National Central Library: Mr. J. E. Hodgson (Honorary Librarian).

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Students' Section: Mr. J. C. Hardman (Honorary Secretary).

MEMBERSHIP.

The membership of the Society for 1936 shows an increase of 189 over 1935, as against an increase of 77 in 1935 over the previous year. The figures in brackets give the membership in 1935. The membership of the Society is now the greatest in its history and there is every sign that it will continue to increase at its present rate for some time to come.

The Council note with satisfaction that there is a considerable increase in the numbers of members joining from official sources, much of which is due to the personal influence of the President, Mr. H. E. Wimperis.

	No. of Members.		Honorary & Life Members.		Suspended.		Total.	
Fellows	144	(135)	23	(23)	1	(3)	168	(161)
Members	54	(54)	1	(1)	1	(2)	56	(57)
Associate Fellows	526	(475)	6	(5)	8	(10)	540	(490)
Associate Members ...	134	(116)	—	(—)	11	(4)	145	(120)
Associates	220	(198)	3	(3)	13	(14)	236	(215)
Companions	107	(101)	8	(9)	7	(3)	122	(113)
Founder Members	24	(26)	1	(1)	1	(—)	26	(27)
Students	442	(348)	—	(—)	33	(48)	475	(396)
Temp. Hon. Members ...	—	(—)	26	(29)	—	(—)	26	(29)
	1651	(1453)	68	(71)	75	(84)	1794	(1608)
Less Joint Members ...	25	(28)					25	(28)
	1626	(1425)	68	(71)	75	(84)	1769	(1580)

DONATIONS.

The Council have to thank the Air Ministry for the twelfth year in succession for their generous donation of £250 to the Funds of the Society, and the Society of British Aircraft Constructors, also for the twelfth year in succession for their generous donation of £250.

The Council also wish particularly to thank Mr. C. R. Fairey, M.B.E., F.R.Ae.S., and Mr. F. Handley Page, C.B.E., F.R.Ae.S., for their generous joint donation of £750 a year for seven years under a deed of gift. The first payments under the deed were made in the year under review.

The donations which have been received are enabling the Society to expand steadily, to publish in the JOURNAL more scientific and technical papers, and to fulfil the objects for which it was founded, "the advancement of aeronautical science and engineering."

ENDOWMENT FUND.

The table below gives the progress of the Endowment Fund:—

	£	s.	d.
December, 1926	575	0	0
December, 1927	597	2	0
December, 1928	1,047	18	0
December, 1929	1,077	6	0
December, 1930	1,265	10	0
December, 1931	1,935	10	0
December, 1932	2,196	2	0
December, 1933	9,716	19	5
December, 1934	10,131	14	11
December, 1935	10,895	10	7
December, 1936	11,138	16	7

The Endowment Fund Trust Deed specifically ensures that every contribution to the Fund will be devoted to the provision of the Society's own building. The Council have had under anxious consideration during 1936 many schemes for new premises for the Society and have appointed a special Development Committee to consider the problem in all its aspects. The lease of the present premises comes to an end in September, 1937. The final decision must rest upon financial considerations and it is hoped that every member will bear that fact in mind and help the Endowment Fund to the best of his ability.

LIBRARY.

The Council have to thank Mr. J. E. Hodgson, Hon. F.R.Ae.S., for the thirteenth year in succession for the valuable help and advice which he has given to the Society.

The Society's collection of slides has been increased during the year and many outstanding gaps have been filled. The slide collection is kept as up to date as possible so that now there are few aspects of aviation for which slides cannot be supplied to members. The collection is the largest aeronautical slide collection in the world outside Government sources and the demand made upon it has been rapidly increasing as its unique value has become more widely known. The Council wish particularly to thank those members and firms who have so willingly and generously helped to add to the collection. During the year, in particular, the collection has been enriched by a large number of remarkable slides of bird flight and, by the kindness of the Meteorological Office, a number of slides of cloud formation.

Side by side with the slide collection the Society's collection of photographs continues to increase and is in many ways unique.

The technical index which was begun a few years ago has proved of steadily increasing value. It is hoped with an increased income of the Society, to make the index considerably larger and more useful. The number of questions on all aspects of aviation, which are now being answered for members, is evidence of the value of the index, however.

GARDEN PARTY.

The Society held its Annual Garden Party on Sunday, May 10th, 1936, at the Great West Aerodrome, near Hayes, again by kind permission of Mr. C. R.

Fairey, M.B.E., F.R.Ae.S., Past-President of the Society. It proved to be even more successful than the previous year and over 2,300 members and their guests attended. A full report and a list of some of the members and guests was published in the JOURNAL for December, 1936.

WILBUR WRIGHT MEMORIAL LECTURE.

The Twenty-Fourth Wilbur Wright Memorial Lecture, entitled "Surface Films and Lubrication," by Mr. D. R. Pye, M.A., Sc.D., M.I.Mech.E., F.R.Ae.S., was delivered before the Society on May 21st, 1936, in the Aeronautical Section of the Science Museum, South Kensington. As in previous years the Annual Council Dinner preceded the lecture which was followed by a Reception. The various medals and awards made during the year were presented to the recipients. A full report of the lecture and Reception was published in the Journal for October, 1936.

LECTURE PROGRAMME.

A full list of lectures delivered before the Society, and of the principal lectures delivered before the Branches, were given in the JOURNAL for December, 1936. In addition, the following lectures have been delivered or arranged for during the remainder of the present Session:—

Jan. 8th.—F. R. Banks, F.R.Ae.S., "High Duty Aero Engines and Fuels." A Joint Lecture with the Institution of Petroleum Technologists and the Institution of Automobile Engineers.

Jan. 14th.—Dr. C. H. Desch, "Magnesium Alloys."

Jan. 28th.—Dr. N. A. de Bruyne, "Plastic Materials for Aircraft Construction."

Feb. 11th.—Mr. F. W. Meredith, B.A., and Mr. P. A. Cooke, O.B.E., M.C., "Aeroplane Stability and the Automatic Pilot."

Feb. 18th.—Mr. A. H. R. Fedden, M.B.E., M.I.A.E., M.S.A.E., F.R.Ae.S., "Trend of Air-Cooled Engines in the next Five Years."

Feb. 25th.—Mr. N. S. Muir, B.Sc., A.M.I.Mech.E., "Engine Power Measurements in Flight."

March 11th.—Major B. C. Carter, M.I.Mech.E., F.R.Ae.S., A.R.C.Sc., D.I.C., "Airscrew Blade Vibration."

April 8th.—Mr. A. G. Pugsley, M.Sc., A.M.I.Struct.E., "Control, Surface and Wing Stability Problems."

April 22nd.—Mr. G. J. Mead, A.F.R.Ae.S., "Power Plant Trends."

April 26th.—Mr. H. E. Wimperis, C.B., C.B.E., M.A., M.I.Mech.E., F.R.Ae.S., "The Natural Limits of Human Flight."

May 27th.—Dr. Theodor von Kármán, F.I.Ae.S. (Wilbur Wright Lecture), "Turbulence."

LECTURES BEFORE THE BRANCHES.

Jan. 5th.—Lecture before the Bristol Branch, by Mr. W. C. Devereux, A.F.R.Ae.S., on "Light Alloys."

Jan. 13th.—Lecture before the Southampton Branch, by Squadron Leader R. S. Booth, A.F.C., R.A.F., on "Airships."

Jan. 14th.—Lecture before the Yeovil Branch by a Representative of Mouldrite, Limited, on "Plastics."

Jan. 14th.—Lecture before the Portsmouth Branch, by Mr. I. J. Gerard, M.Sc., A.M.I.C.E., A.F.R.Ae.S., "Stressed Skin Construction."

Jan. 14th.—Lecture Before the Manchester Branch, by Mr. R. G. Robertson, B.A., A.M.Inst.C.E., on "Gliding and Soaring."

Jan. 21st.—Lecture before the Portsmouth Branch by a member of Titanine, Limited.

Jan. 21st Lecture before Coventry Branch, by Mr. L. A. Sweny, on "Air Route and Aerodrome Control."

Jan. 26th.—Lecture before the Bristol Branch, by Mr. H. B. Howard, F.R.Ae.S., on "Martlesham Methods of Aircraft Testing."

Jan. 28th.—Lecture before the Yeovil Branch, by Mr. N. C. Wilson, on "Press Tool Work."

Jan. 28th.—Lecture before the Portsmouth Branch, by Mr. C. F. Snowden Gamble, on "Commercial Aviation."

Feb. 4th.—Lecture before the Portsmouth Branch, by Mr. M. Langley, A.M.I.N.A., M.I.Ae.E., on "The Use of Plastics in Aircraft Structures."

Feb. 10th.—Lecture before the Southampton Branch by a member of the Staff of Sperry Gyroscope Company, on "Blind Flying."

Feb. 11th.—Lecture before the Yeovil Branch, by Mr. W. C. Devereux, A.F.R.Ae.S., on "High Duty Alloys and their Radiological Testing."

Feb. 11th.—Lecture before the Portsmouth Branch, by Captain F. S. Barnwell, O.B.E., A.F.C., B.Sc., F.R.Ae.S., on "The Design of High Altitude Aircraft."

Feb. 11th.—Lecture before the Manchester Branch, by Mr. J. L. Nayler, M.A., F.R.Ae.S., on "The Problem of Bird Flight and the Aeroplane."

Feb. 14th.—Lecture before the Portsmouth Branch, by Mr. M. Langley, M.I.Ae.E., A.M.I.N.A., on "The Use of Plastics in Aircraft Structures."

Feb. 16th.—Lecture before the Bristol Branch, by Mr. C. P. Lipscomb, A.F.R.Ae.S., on "The Design of the Empire Flying Boats."

Feb. 18th.—Lecture before the Coventry Branch, by Mr. A. H. Davis, of the National Physical Laboratory, on "Silencing Aircraft."

Feb. 18th.—Lecture before the Portsmouth Branch, by Flight Lieut. H. F. Jenkins, on "Blind Flying."

Feb. 25th.—Lecture before the Yeovil Branch, by Mr. L. H. Pomeroy, M.I.M.E., on "The Reactions of an Automobile Engineer to Aircraft Engines."

March 10th.—Lecture before the Southampton Branch by Mr. F. M. Owner, M.Sc., A.F.R.Ae.S., on "Factors Controlling Aero Engine Development."

March 11th.—Lecture before the Manchester Branch, by Mr. S. M. Parker, on "Hydraulic Services in Aircraft."

March 18th.—Lecture before the Coventry Branch, by Squadron Leader Godsave, on "Navigation."

April 14th.—Lecture before the Southampton Branch, by Captain A. Graham Forsyth, on "Modern Airscrew Development."

April 15th.—Lecture before the Coventry Branch, by Mr. S. J. Hartley, B.Sc., on "Production and Inspection Methods Applied to Screw Threads."

STUDENTS' SECTION.

A Report of the activities of the Students' Section for the Session 1935-1936 was published in the December, 1936, JOURNAL. The following is a list of lectures and visits to works arranged for the 1936-1937 Session:—

MEETINGS.

Oct. 1st (Thurs.).—Annual General Meeting.

Oct. 15th (Thurs.).—Inaugural Address: "Recent Developments in Aeronautical Research." Mr. E. F. Relf, A.R.C.Sc., F.R.Ae.S. Chairman: Mr. H. T. Tizard, C.B., A.F.C., F.R.S., F.R.Ae.S.

Nov. 3rd (Tues.).—"Technical Aeronautics in Australia." Mr. J. V. Connolly, B.E., A.F.R.Ae.S. Chairman: Mr. S. H. Evans, A.F.R.Ae.S., M.I.Ae.E.

Dec. 1st (Tues.).—" Stressed Skin Construction." Mr. C. Moore, B.Sc., A.F.R.Ae.S. Chairman: Mr. I. J. Gerard, M.Sc., A.M.Inst.C.E., A.F.R.Ae.S.

Dec. 15th (Tues.).—" Fuels for Aero Engines." Mr. C. H. Barton, M.A. (Joint Meeting with the Graduates' Section of the Institution of Automobile Engineers and the Students' Section of the Institute of Petroleum Technologists.)

Jan. 5th (Tues.).—" Aircraft Performance Estimation." Mr. C. O. Vernon, Stud.R.Ae.S.I. Chairman: Mr. R. S. Stafford, A.F.R.Ae.S.

Jan. 19th (Tues.).—" Critical Speeds of Monoplanes." Mr. J. Hanson, B.Sc. Chairman: Mr. A. G. Pugsley, M.Sc., A.M.I.Struct.E.

Feb. 2nd (Tues.).—" Bird Flight in its Relation to Aeronautical Engineering," by Captain J. Laurence Pritchard, Hon. F.R.Ae.S. Chairman: J. L. Nayler, Esq., F.R.Ae.S.

Feb. 16th (Tues.).—" Production of Light Metal-Clad Aircraft." Mr. I. Waddington, B.A., A.F.R.Ae.S. Chairman: The Lord Sempill, A.F.C., F.R.Ae.S.

March 2nd (Tues.).—" Flaps." Mr. J. Hardman. Chairman: Mr. W. R. Andrews, A.F.R.Ae.S.

March 16th (Tues.).—Extended discussion on the paper " Stressed Skin Construction," read by C. Moore.

April 6th (Tues.).—Debate: " Speed *v.* Safety in Civil Aircraft Design." Chairman: Captain J. Laurence Pritchard, Hon. F.R.Ae.S.

April 20th (Tues.).—" Aircraft Design from a Pilot's Point of View." Captain J. H. Cordes (Chief Test Pilot, Messrs. Handley Page, Limited).

VISITS.

Oct. 17th (Sat.).—10.0 a.m., Short Brothers, Limited, Rochester. 3.0 p.m., Pobjoy Airmotors and Aircraft, Limited.

Nov. 7th (Sat.).—3.0 p.m., De Havilland Aircraft Company (Engine Department), Stag Lane, Edgware, Middlesex.

Dec. 5th (Sat.).—3.0 p.m., Smith's Instruments, Limited, Edgware Road, Cricklewood, N.W.2.

Jan. 27th (Wed.).—2.45 p.m., Ford Motor Works, Dagenham.

Feb. 20th (Sat.).—2.30 p.m., The Ratcliffe Tool Co., Ltd., Gorst Road, Park Royal, Great West Road, N.W.10.

March 20th (Sat.).—3.0 p.m., The Airscrew Company, Weybridge.

April 24th (Sat.).—9.30 a.m., Royal Aircraft Establishment, South Farnborough. (British Subjects only.)

May 22nd (Sat.).—2.30 p.m., Gatwick Airport. (Party Tickets 3/6 approx.)

June 19th (Sat.).—10.0 a.m., Airspeed (1934), Limited, Portsmouth. 3.0 p.m., Saunders Roe, Limited, Isle of Wight.

PUBLIC SCHOOLS LECTURES.

The year under review is the sixth year in succession that lectures have been arranged before the public schools and other educational centres. The demand for these lectures, one of the most valuable forms of propaganda, is evidence of their interest and popularity.

The Council wish particularly to record their thanks to all those members who have given so much of their time to the delivering of one or more of the schools lectures. Many special lectures, outside the standard list, have been delivered on the Society's behalf and it is hoped to prepare a number of other regular lectures so that as wide a field as possible may be covered. The standard lectures are complete in themselves so that lecturers have the minimum amount of actual preparation. Each lecture is arranged so as to take one hour to deliver.

In addition to the list published in the December JOURNAL for 1936, the following have been arranged for, or delivered, in 1937:—

Jan. 6th.—Lecture before the Literary Society, Hatfield Heath, by Mr. H. T. Winter, on "A Trip into the Stratosphere."
Jan. 26th.—Lecture before Hersham Guild, by Captain J. Laurence Pritchard, Hon. F.R.Ae.S., on "Modern Aeroplanes."
Jan. 29th.—Lecture before Birkenhead School, by Mr. R. A. Mettam, F.R.Ae.S., on "How an Aeroplane is Made and Flies."
Feb. 2nd.—Lecture before Harringay Literary Society, by Mr. H. T. Winter, on "A Trip into the Stratosphere."
Feb. 5th.—Lecture before Kenrick Technical College, by Mr. A. N. Jackson, A.F.R.Ae.S., on "How an Aeroplane is Made and Flies."
Feb. 6th.—Lecture before Eastbourne College, by S. Scott-Hall, A.F.R.Ae.S., on "The Evolution of Aeronautics."
Feb. 9th.—Lecture to King Edward School, Southampton, by Mr. T. Tanner, A.F.R.Ae.S., on "How an Aeroplane Flies."
Feb. 11th.—Lecture before the Hackney Central Library, by Mr. H. T. Winter, on "A Trip into the Stratosphere."
Feb. 25th.—Lecture before the Hendon Public Library, by Mr. H. T. Winter, on "A Trip into the Stratosphere."
March 4th.—Lecture before the City and Guilds Engineering Society, by Captain J. Laurence Pritchard, Hon. F.R.Ae.S., on "Queer Flying."
March 5th.—Lecture before Balshaws Grammar School, by Mr. C. L. Old, on "How an Aeroplane is Made and Flies."

BRANCHES.

There are now eleven Branches of the Society and the Council wish to congratulate all concerned with their administration, on the excellence of their lecture programmes and progress which has been made during the past year. Much of the success of a Branch depends upon its executive officers, particularly its Chairman, Committee and Honorary Secretary, and the Council wish to place on record their thanks for the work they have done to further the progress of the Branches. The following is a list of Branches:—

Australian Branch.
Chairman: T. D. J. Leech, B.Sc., B.E., M.I.Ae.E.
Hon. Secretary: Philip R. Vyner, A.M.I.Ae.E.
Address: Science House, Gloucester and Essex Streets, Sydney, Australia.

Bristol Branch.
Chairman: A. H. R. Fedden, M.B.E., M.I.A.E., M.S.A.E., F.R.Ae.S.
Hon. Secretary: H. Yendall, Esq.
Address: 76, Redcatch Road, Knowle, Bristol 4.

Cambridge University Engineering and Aeronautical Society (affiliated to the Royal Aeronautical Society).
President: R. H. Angus, Esq., M.A.
Aeronautical Section—President: A. I. S. Debenham, Esq.
Secretary: J. G. Lubbock, Esq.
Address: Trinity College.

Coventry Branch.
Chairman: Major B. W. Shilson, O.B.E., M.I.Mech.E., F.R.Ae.S.
Hon. Secretary: E. D. Keen, Esq., B.Sc., A.M.I.Ae.E.
Address: Sir W. G. Armstrong-Whitworth Aircraft, Limited, Coventry.

Gloucester and Cheltenham Branch.

President: T. O. M. Sopwith, Esq., C.B.E., F.R.Ae.S.
Chairman: H. P. Folland, Esq., M.B.E., F.R.Ae.S., M.I.Ae.E.
Hon. Secretary: F. B. Ford, Esq., A.F.R.Ae.S.
Address: St. Margaret, Brockworth, Nr. Gloucester.

Hull and Leeds Branch.

Chairman: Major F. A. Bumpus, B.Sc., F.R.Ae.S.
Hon. Secretary: G. B. Fenton, Esq., A.F.R.Ae.S.
Address: c/o Fairview, Brough, Yorks.

Manchester Branch.

President: Sir John D. Siddeley, C.B.E., J.P., F.R.Ae.S.
Chairman: R. Chadwick, Esq., A.F.R.Ae.S.
Hon. Secretary: J. E. A. Waterfall, Esq.
Address: 7, St. Andrew's Road, Stretford, Manchester.

Montreal Branch.

Address of Hon. Secretary: Engineering Institute of Canada, 2050, Mansfield Street, Montreal, Canada.

Ottawa Branch.

Hon. Secretary: Squadron Leader A. Ferrier, A.F.R.Ae.S.
Address: 370, Driveway, Ottawa, Ontario, Canada.

Portsmouth Branch.

President: A. H. Tiltman, Esq., B.Sc., F.R.Ae.S.
Chairman: H. W. Denny, Esq.
Hon. Secretary: H. I. Birds, Esq., B.Sc., A.F.R.Ae.S.
Address: "Elmcroft," Victoria Road North, Southsea, Hants.

Southampton Branch.

Chairman: Wing Comdr. T. R. Cave-Browne-Cave, C.B.E., M.I.Mech.E., F.R.Ae.S.
Hon. Secretary: T. Tanner, Esq., A.C.G.I., D.I.C., A.F.R.Ae.S.
Address: 1, The Retreat, Southsea, Hants.

Yeovil Branch.

President: Sir Ernest W. Petter, M.I.Mech.E.
Hon. Secretary: H. J. Penrose, Esq., F.R.Ae.S.
Address: Westland Aircraft, Limited, Yeovil, Somerset.

PRESIDENT.

Mr. H. E. Wimperis, C.B., C.B.E., M.A., M.I.E.E., F.R.Ae.S., Director of Scientific Research, Air Ministry, was elected President of the Society for the year 1936-1937, at the Council Meeting held on May 12th, 1936.

VICE-PRESIDENTS.

Major T. M. Barlow, M.Sc.(Eng.), M.Inst.C.E., M.I.Mech.E., F.R.Ae.S., and Mr. F. Handley Page, C.B.E., F.R.Ae.S., were elected Vice-Presidents of the Society at a Council Meeting held on May 12th, 1936.

JOURNAL.

In the last Annual Report of the Council it was stated that there was every prospect during 1936 of decreasing the heavy loss of the JOURNAL. During the year the JOURNAL has been constantly under review and despite an increase of

nearly ten per cent. in printing orders the loss has been decreased from £1,200 to a little less than £200. This satisfactory decrease has been largely due to a small decrease in printing costs and a large increase in advertising revenue. The arrangements for advertising in the JOURNAL came under the control of the Society at the beginning of 1936 and enabled the Editor to make new and more satisfactory contracts with advertisers.

The present financial position of the JOURNAL holds out every hope that a number of improvements in its format and contents which the Council have had in mind may be soon seriously considered.

JOURNAL ACCOUNT FOR 1936.

	£	s.	d.		£	s.	d.
Stock of JOURNALS and Sundry Publications at 31st December, 1935	350	0	0	Sales of JOURNALS and Sundry Publications for year	1,106	10	6
Printing costs	2,059	15	11	Estimated cost of copies sent to members ...	1,363	19	0
Postages	215	9	11	Advertisement revenue...	1,155	9	9
Back numbers purchased	3	10	0	Stock of JOURNALS and Sundry Publications at 31st December, 1936	250	0	0
Cost of Reviews and Articles	61	15	8				
Profit for year to date...	1,185	7	8				
	£3,875	19	3		£3,875	19	3

FINANCE.

The Balance Sheets, Income and Expenditure Accounts, of Aerial Science, Limited, and of Aeronautical Trusts, Limited, are published in this issue of the JOURNAL. The Council are glad to report that the accounts are in a healthy condition. In view of the heavy expenses which the Society is likely to have to meet in connection with the termination of the lease of its premises in 1937, the Council have scrutinised all items of the expenditure with great care, whilst doing their best to increase the revenue of the Society by increasing the membership, and supporting the Secretary in his efforts, fortunately successful, to make improved arrangements for the advertising columns of the JOURNAL. The revenue from advertising has, they are glad to report, shown a substantial increase. The Council have, moreover, followed the conservative policy of writing down the figure at which the stock of JOURNALS and other publications have hitherto stood in the Balance Sheet.

The accounts now presented show a surplus of income over expenditure of £1,329 1s. 10d. against an excess in the previous year of expenditure over income (after including interest from the Endowment Fund) of £138 19s. 5d.

It is satisfactory that the net cost of the JOURNAL has been reduced from the figure of £1,221 14s. 5d. in 1935 to as little as £178 11s. 3d. in 1936. It will be noted that there is an increase of some £300 in annual subscriptions and the Council hope that all members will do their best to assist in the growth of revenue from this source in the coming years.

SOLICITOR.

Mr. Lawrence A. Wingfield, M.C., D.F.C., A.R.Ae.S.I., continues to act as Solicitor to the Society. The Council during the year have had the benefit of his advice upon legal matters, which is freely given on Committees and at the Council Meetings, and they wish particularly to thank him for the help he has given to the Society.

AERONAUTICAL

Balance Sheet,

	£ s. d.	£ s. d.	£ s. d.
Share Capital—			
Authorised—40 Shares of 1/- each	... ...	2 0 0	
Issued—21 Shares of 1/- each	... ...	1 1 0	
Less—Calls in arrear	... ...	1 1 0	— — —
Pilcher Memorial Fund—			
Capital Account—As at 31st December, 1935		99 14 0	
Income Account—Balance at 31st December, 1935 ...	35 4 4		
Add Income for year to date...	4 0 8	39 5 0	138 19 0
Usborne Memorial Fund—			
Capital Account—As at 31st December, 1935		109 2 5	
Income Account—Balance at 31st December, 1935 ...	37 11 0		
Add Income for year to date	3 19 0	41 10 0	150 12 5
Herbert Akroyd Stuart Fund—			
Capital Account—As at 31st December, 1935		688 19 0	
Income Account—Balance at 31st December, 1935 ...	154 16 7		
Add Income for year to date	23 18 0	178 14 7	867 13 7
R.38 Memorial Fund—			
Capital Account—As at 31st December, 1935		978 3 10	
Income Account—Balance at 31st December, 1935 ...	348 8 0		
Add Surplus of Income over Expenditure for year to date	10 8 10	358 16 10	1337 0 8
Edward Busk Memorial Fund—			
Capital Account—As at 31st December, 1935		449 6 1	
Income Account—Balance at 31st December, 1935 ...	88 12 9		
Less Excess of Expenditure over Income for year to date	0 4 1	88 8 8	537 14 9
Wilbur Wright Memorial Fund—			
Capital Account—As at 31st December, 1935		1298 9 9	
Income Account—Balance at 31st December, 1935 ...	109 4 11		
Add Surplus of Income over Expenditure for year to date	8 10 3	117 15 2	1416 4 11
Simms Gold Medal Fund—			
Capital Account—As at 31st December, 1935		250 0 0	
Less—Income Account Deficiency at 31st December, 1935	11 9 0		
Add Excess of Expenditure over Income for year to date	4 13 6	16 2 6	233 17 6
Royal Aeronautical Society Endowment Fund—			
Capital Account—Balance at 31st December, 1935 ...		10895 10 7	
Add Donations received during year		3 18 0	
Entrance Fees received during year		239 8 0	— — — 11138 16 7
			£15820 19 5

We report to the Members of Aeronautical Trusts, Ltd., that we have examined the above explanations we have required. We are of opinion that the Balance Sheet is properly drawn up December, 1936, according to the best of our information and the explanations given to us and as

3, Frederick's Place, Old Jewry, London, E.C.2.
25th February, 1937.

TRUSTS LIMITED

31st December, 1936.

	£ s. d.	£ s. d.
Pilcher Memorial Fund—		
£115 6s. 10d. 3½ % War Loan at cost	116 5 0	
Cash at Bank	22 14 0	
		138 19 0
Usborne Memorial Fund—		
£113 3½ % War Loan at cost	114 11 1	
Cash at Bank	36 1 4	
		150 12 5
Herbert Akroyd Stuart Fund—		
£683 1s. 0d. 3½ % War Loan at cost	698 19 0	
Cash at Bank	168 14 7	
		867 13 7
R.38 Memorial Fund—		
£1048 11s. 2d. 3½ % War Loan at cost	1098 18 10	
Cash at Bank	238 1 10	
		1337 0 8
Edward Busk Memorial Fund—		
£284 4s. 2d. 3½ % War Loan at cost	284 4 2	
£217 London Transport 4½ % "A" Stock at cost	199 4 6	
	483 8 8	
Cash at Bank	50 19 1	
Amount due for refund of Income Tax	3 7 0	
		537 14 9
Wilbur Wright Memorial Fund—		
£1047 6s. 7d. 3½ % Conversion Stock, at cost	800 0 0	
£550 Canada 4 % Stock, at cost	531 10 9	
	1331 10 9	
Cash at Bank	102 7 2	
Amount due for refund of Income Tax	4 19 0	
	1438 16 11	
Less—Amount owing to Aerial Science, Ltd.	22 12 0	
		1416 4 11
Simms Gold Medal Fund—		
£287 16s. 1d. India 4½ % Stock, 1958/68, at cost	250 0 0	
Cash at Bank	16 14 0	
	266 14 0	
Less—Amount owing to Aerial Science, Ltd.	32 16 6	
		233 17 6
Royal Aeronautical Society Endowment Fund—		
Investments at Cost—		
£3504 2s. 8d. 3½ % Conversion Stock	3192 5 1	
£4100 L. & N.E. Rly. 3 % Debentures	3162 6 3	
£3100 L.M. & S. Rly. 4 % Debentures	3162 19 9	
£862 16s. 8d. Manchester 3 % Stock, 1952/55	870 9 8	
£629 16s. 4d. London County 2¾ % Stock, 1960/70	600 0 0	
	10988 0 9	
Cash at Bank	218 0 0	
Amount due for refund of Income Tax	84 12 5	
	11290 13 2	
Less—Amount due to Aerial Science, Limited	151 16 7	
		11138 16 7
		£15820 19 5

Balance Sheet with the books of the Company and have obtained all the information and so as to exhibit a true and correct view of the state of the Company's affairs as at 31st shown by the books of the Company.

PRICE, WATERHOUSE & CO.

AERONAUTICAL

INCOME & EXPENDITURE ACCOUNTS

Pilcher

	£ s. d.
To Income for year carried to Balance Sheet...	4 0 8
	£4 0 8

Usborne

To Income for year carried to Balance Sheet	3 19 0
	£3 19 0

Herbert Akroyd

To Income for year carried to Balance Sheet	23 18 0
	£23 18 0

R.38

To 1936 Award	26 5 0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	10 8 10
	£36 13 10

Edward Busk

To 1936 Award	21 0 0
	£21 0 0

Wilbur Wright

To 1936 Award	50 0 0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	8 10 3
	£58 10 3

Simms Gold

To 1936 Award	17 12 6
	£17 12 6

Royal Aeronautical Society

To Legal Expenses	6 6 0
,, Surplus of Income over Expenditure for year transferred to Aerial Science, Limited	388 16 7
	£395 2 7

TRUSTS LIMITED

FOR THE YEAR ENDED 31ST DECEMBER, 1936.

Memorial Fund

	£ s. d.
By Interest on Investments (gross)	4 0 8
	£4 0 8

Memorial Fund

By Interest on Investments (gross)	3 19 0
	£3 19 0

Stuart Fund

By Interest on Investments (gross)	23 18 0
	£23 18 0

Memorial Fund

By Interest on Investments (gross)	36 13 10
	£36 13 10

Memorial Fund

By Interest on Investments (*less* Tax)...	17 8 11
,, Refund of Income Tax	3 7 0
,, Balance of Expenditure over Income for year carried to Balance Sheet	0 4 1
	£21 0 0

Memorial Fund

By Interest on Investments (*less* Tax)	53 11 3
,, Refund of Income Tax	4 19 0
	£58 10 3

Medal Fund

By Interest on Investments (gross)	12 19 0
,, Balance of Expenditure over Income for year carried to Balance Sheet	4 13 6
	£17 12 6

Endowment Fund.

By Interest on Investments (less Tax)	310 10 2
,, Refund of Income Tax	84 12 5
	£395 2 7

AERIAL SCIENCE, LIMITED

Balance Sheet,

	£ s. d.	£ s. d.
Share Capital—		
Authorised—		
20 Shares of 1/- each	1 0 0	
999 Shares of £1 each	999 0 0	
	1000 0 0	
Issued—		
19 Shares of 1/- each, fully paid		0 19 0
Sundry Creditors		473 5 0
Subscriptions and Other Amounts Received in Advance		375 2 0
Income and Expenditure Account—Balance at 31st December, 1935	1071 13 6	
Add—Surplus of Income over Expenditure for year to date	1579 1 10	
		2650 15 4
		£3500 1 4

We report to the Members that we have examined the above Balance Sheet with the Books are of the opinion that the Balance Sheet is properly drawn up so as to exhibit a true and correct information and the explanations given to us and as shown by the Books of the Society.

3, Frederick's Place, Old Jewry, London, E.C.2.

25th February, 1937.

Income and Expenditure Account

Dr.	£ s. d.
To Office Rent, Heating, Lighting and Insurance	576 7 5
,, Salaries	1256 4 1
,, Printing and Stationery	492 6 1
,, Postages, &c....	182 12 5
,, Office Expenses	530 18 3
,, Meetings	122 8 7
,, Dinners and Receptions	209 10 1
,, Estimated Cost of Journals sent to Members	1363 19 0
,, Library Expenses	40 18 11
,, Slides and Photographs	57 18 10
,, Audit Fee	31 10 0
,, Legal Expenses	12 12 0
,, Prizes and Donations	35 5 6
,, Examination Expenses (*Less* Fees Received)	7 15 0
,, School Lectures	22 13 1
,, Subscriptions Written off	62 17 0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	1579 1 10
	£6584 18 1

(The Royal Aeronautical Society).

31st December, 1936.

	£	s.	d.
Office Furniture, Printed Books, Bindings, Old Prints, etc., at cost, as at 31st December, 1935	453	19	6
Stock of JOURNALS *and other Publications*	250	0	0
Sundry Debtors, including Subscriptions owing	1070	9	11
Investments at Cost—			
£1504 15s. 11d. Manchester Corporation 3 % Red. Consd. Stock, 1952/55 (Market Value at 31st December, 1936) £1519 17s. 0d.	1518	3	3
Cash at Bank and in Hand	207	8	8
	£3500	1	4

of the Society, and have obtained all the information and explanations we have required. We view of the state of the Society's affairs as at 31st December, 1936, according to the best of our

(Signed) PRICE, WATERHOUSE & CO.

for the Year Ending 31st December, 1936.

Cr.	£	s.	d.	£	s.	d.
By Annual Subscriptions				3706	13	3
,, Interest on Investments (*Less* Tax)	34	8	6			
,, Income Tax Recovered	19	12	0			
,, Interest on Endowment Fund Investments (*Less* Expenses) ...	388	16	7			
				442	17	1
,, Donations				1250	0	0
,, Profit on Journal and Sundry Publications (after crediting £1363 19s. 0d., Estimated Cost of Journals sent to Members as *per contra*)				1185	7	9
				£6584	18	1

HONORARY TREASURER.

The Honorary Treasurer, Major D. H. Kennedy, O.B.E., F.R.Ae.S., completed this year ten years' continuous service as Honorary Treasurer and Chairman of the Finance Committee. The Finance Committee during that period has held regular monthly meetings, and the Council wish to thank very specially the Honorary Treasurer for the great amount of time which he has so willingly given to the Society over the past ten years.

HONORARY ACCOUNTANT.

The Honorary Accountant, Mr. A. N. D. Smith, completes his ninth year of office. Mr. Smith has largely been concerned with income tax questions as relating to the Society and with the development of a Pensions Fund, and his help and advice have proved invaluable, saving the Society many hundreds of pounds. The Council wish to thank him for the services he has rendered to the Society in this way.

SPECIAL GENERAL MEETING.

At the Annual General Meeting held on March 30th, 1936, a resolution was passed asking the Council to consider the formation of a new Graduate grade and if thought fit to call a Special General Meeting to alter the Rules accordingly.

The Council called a Special General Meeting on Thursday, 21st January, 1937, and new Rules were unanimously passed to the effect that "Graduates shall be persons not under 21 years of age and not more than 26 years of age (except in such cases as the Council may determine) who have passed the Associate Fellowship or Associate Membership examination or such exempting examinations as are approved by the Council from time to time and have satisfied the Council that they have received or are receiving such training in the design or in the construction of such works as are comprised within the profession of aeronautics; or in the application to aeronautics of special branches of science, mathematics or engineering; or in the development of the science of aeronautics; or serving as a pilot, engineer, or navigator of aircraft; or training for or being employed as a lecturer of aeronautics in a college which has courses leading to a degree recognised by the Council as exempting from the Associate Fellowship or Associate Membership examinations."

The complete detailed alterations of the Rules have now been incorporated in the present published Rules.

At the same Special General Meeting, Rule 83 was altered to read as follows:—

> "At the Council Meeting immediately preceding the Annual General Meeting the Council shall appoint not less than three Scrutineers from those members of the Council who are not nominated for election. The Scrutineers shall present themselves at the Offices of the Society on the day of the Annual General Meeting and count the votes. The Report of the Scrutineers shall be handed to the Chairman of the Meeting immediately before the meeting begins."

SECRETARY.

Captain Pritchard has continued his efficient and zealous work as Secretary and Editor of the JOURNAL. The President and Council desire to put on record their keen appreciation of his services.

STAFF.

Upon the efficiency of the Staff must depend largely the smooth running of the Society and the success of the carrying out of the policies of the Council. In

Miss F. Barwood, who is in charge in the absence of the Secretary, Miss B. Voyce, responsible for the Society's accounts, Miss R. Parkes, who is responsible for a greater part of the clerical work, and Mr. McWilliam, responsible for the JOURNAL advertising, slides and photographs, the Society has an extremely efficient Staff, whose continual keen interest in the work of the Society has enabled it to be administered on a more economical basis than that of any corresponding society.

REVIEW.

My Flying Life.

Prepared under the personal supervision of the late Sir Charles Kingsford-Smith. Published by Andrew Melrose, Ltd. Price 16/-.

The pioneer pilot is, necessarily, a special type of human being. He is akin to those who first drove bullock wagons across the African veldt, to those Elizabethan navigators who sailed their small ships into unknown seas, and to those who make it their life's work to extend human knowledge of the North and South Polar regions. The motive in each case seems to be the same, an irresistible urge to be the first to do something which the pioneer knows to be important, or to go somewhere where nobody has ever been before.

Among such men Sir Charles Kingsford-Smith will always take a high place, his two first crossings of the Pacific Ocean in opposite directions were the hall-marks of his career, and they can sustain comparison with any feat of pioneering which has ever been attempted. Almost every important incident of his life shows the trend of his mind. When there were no more oceans to conquer, he pioneered commercial air services between Australia and New Zealand, and when he had nothing else to do he was always anxious to beat the latest aeroplane record between England and Australia, and it was in the last of these attempts that he lost his life.

Like most such men he knew little about financial matters. When he had a big flight on his mind he always seems to have been able to get the money from someone, and it must be that he succeeded in communicating some of his enthusiasm to those who knew him, for, on several occasions, when the financial difficulties of a flight seemed hopeless, the necessary money seemed to drop out of the sky. But, although he managed to finance his flights he could never attract any money to himself, and on several occasions during his life he was compelled to tour with his aeroplane, giving short distance flights for small fees to the inhabitants of towns and cities.

A thing which he always did supremely well was the organisation of his flights, nothing but the best was good enough for him. He always wanted and obtained the best aeroplane, engineers, and instruments that were available and left nothing to chance except such matters that foresight could not provide for. This is what he says about such matters.

" Personally, I have always endeavoured to avoid so-called ' adventures.'—My conception of a record flight is of a programme properly prepared beforehand, which is accomplished to schedule and without incident.—The secret of success in this depends on the perfection of one's plans, the capacity for monotonous endurance, and first-hand knowledge of the territories over which one passes."

But when, in spite of all his precautions, so-called adventures came to him uninvited, he was ready. No man ever had a clearer instinct for doing the best thing in an unexpected emergency. When, on a mail carrying flight between Australia and New Zealand, the propeller came off one of the engines of his three-engined aeroplane, at a moment when he was nearly halfway across the Tasman Sea he acted decisively, and there is no doubt that it was nothing but his nerve and skill that saved the aeroplane and crew, though the mails themselves had to be jettisoned.

It is not stated whether the original manuscripts of this book have been edited, but, if not, it is clear that Sir Charles Kingsford-Smith had a considerable skill with the pen. His English is clear and lucid, and the whole forms a worthy record of a man who deserves to be remembered.

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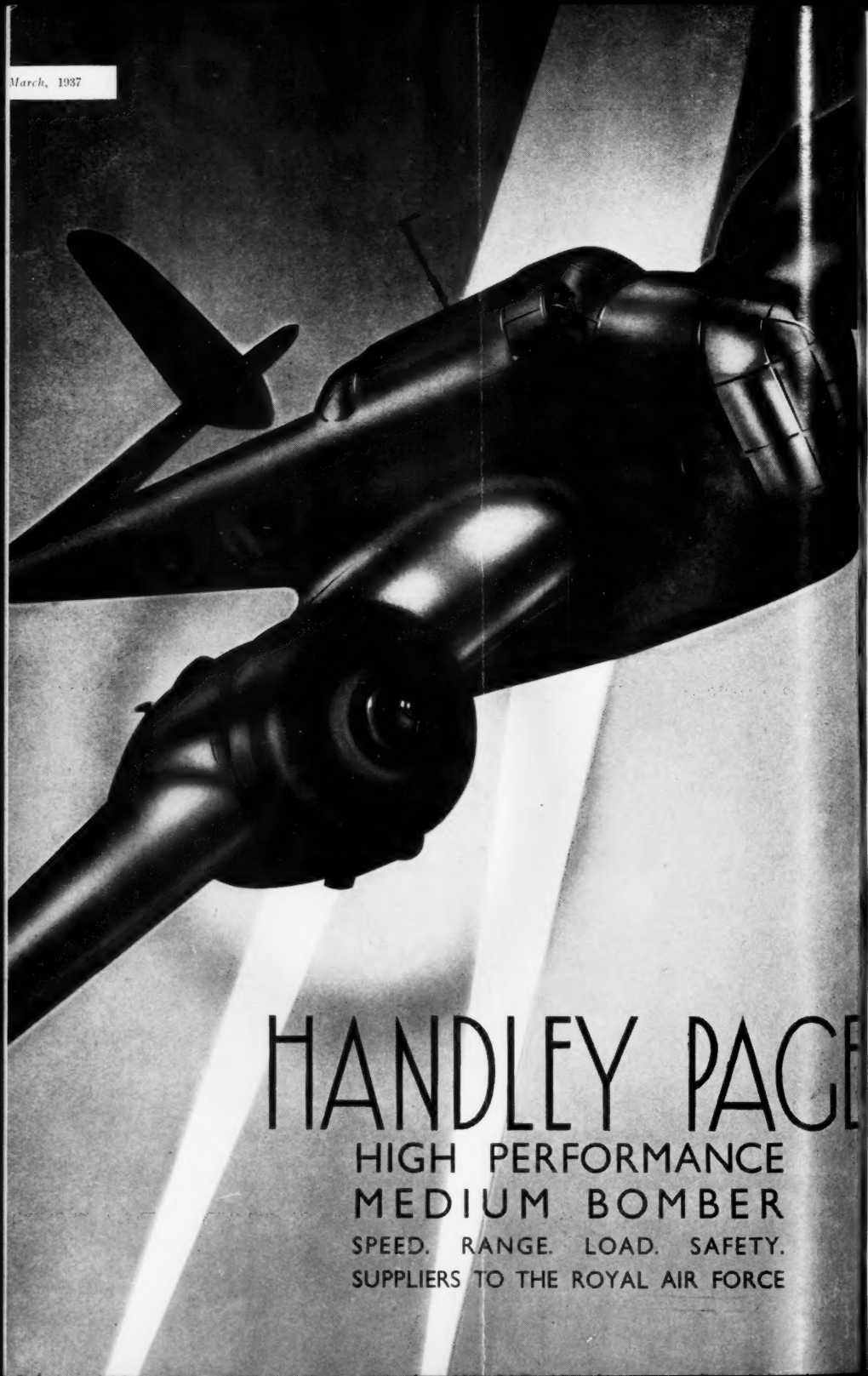
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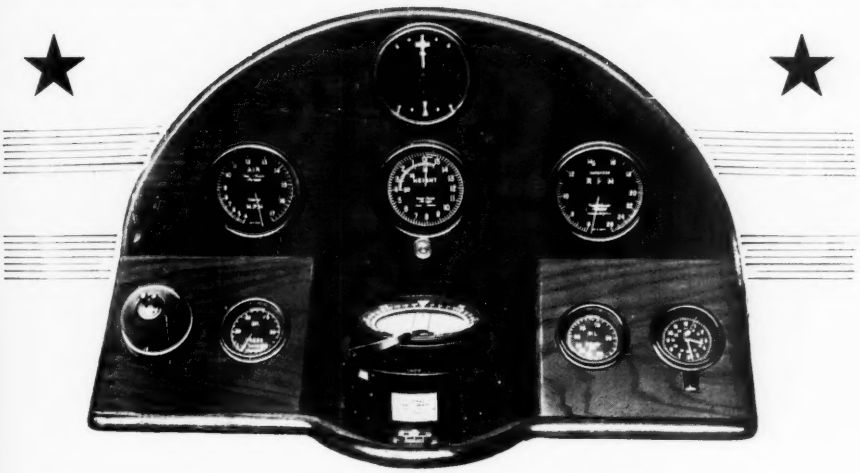

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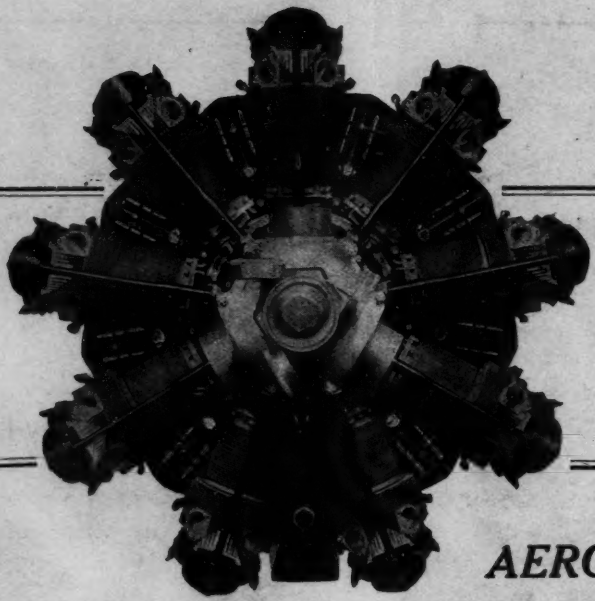

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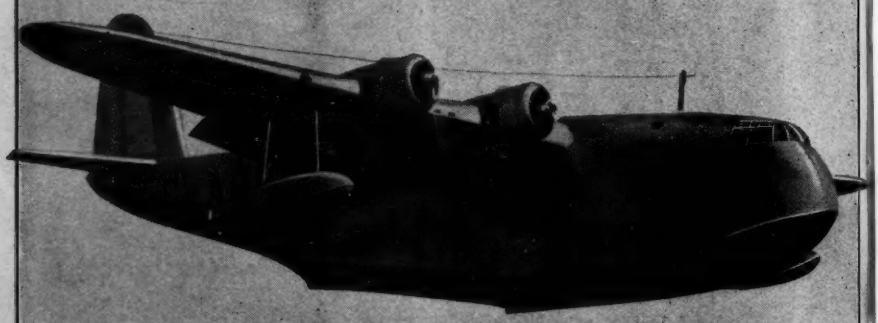

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The 612th Lecture read before the Royal Aeronautical Society since its foundation on January 12th, 1866.

PROCEEDINGS.

A meeting of the Society was held at the Royal Society of Arts, John Street, Adelphi, London, on Thursday, December 10th, 1936. In the chair, Mr. H. E. Wimperis, C.B., C.B.E., M.A., F.R.Ae.S., President of the Society.

The PRESIDENT: He expressed on behalf of the members the great regret of the Royal Aeronautical Society at the death of Senor Juan de la Cierva, who was a very distinguished inventor, perhaps the greatest living Spanish engineer at the time of his death, and a valued Fellow of the Society. Senor Cierva had lectured before the Society three times, and on each occasion he had introduced to their notice some new facet of his work, some new means of obtaining further advance in the direction he had chosen. Senor Cierva had received from the Society its silver medal, the Wakefield gold medal and subsequently the Guggenheim gold medal. Senor Cierva's work and his own, continued the President, had brought them into frequent contact, and he had soon formed the very highest opinion of Senor Cierva's qualities as an engineer, of his amazing ingenuity in overcoming the many problems that arose from day to day, and of his intrepid courage in flying his machines in all stages of their experimental construction. The Council of the Society had already sent a message of high appreciation of Senor Cierva to Senora Cierva, and an expression of their great regret at the loss of so valuable a life.

All present stood for a few moments in silence as a tribute to the late Senor Cierva.

The PRESIDENT: His task of introducing the lecturer that evening was easily performed, because he had nothing to say which was not already perfectly well known to everybody present. Mr. Gouge was one of the leading seaplane designers and constructors in this country and, indeed, in the world, and he had shown, by undertaking the construction of this considerable fleet of flying boats—the Empire flying boats—for Imperial Airways, that he was willing to back his own ideas with almost instant, certainly very rapid, construction.

The following paper was then read: " Recent Progress in the Design of Civil Flying Boats," by A. Gouge.

RECENT PROGRESS IN THE DESIGN OF CIVIL FLYING BOATS.

By A. GOUGE, B.Sc., F.R.Ae.S.

Before reading this paper, I should like to make a brief explanation of my reason for changing the published title.

The original intention was to give a survey of civil flying boats in general, but after due consideration the subject appeared to me to cover far too much ground, unless it was restricted to merely a collection of already published data of past and present aircraft of this type.

Whilst a paper of this nature would, undoubtedly, prove to be of considerable interest, yet, personally, I feel more competent to review the three types of flying boats designed purely for civil use, which have come directly under my supervision during the past eight years.

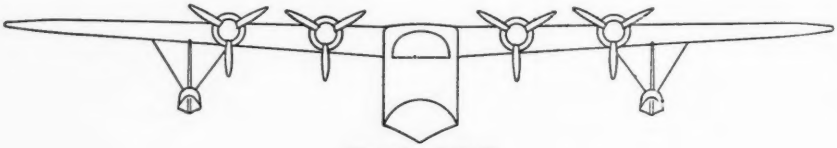
These classes, the " Calcutta," " Kent " and " Empire " boat, are well known to you and have all been designed to meet a commercial specification issued either by the Air Ministry or Messrs. Imperial Airways. They can, therefore, be called civil flying boats in the true sense of the word, and not a develop-

ment from a military type. In the case of the " Calcutta " the reverse has happened in that it has been converted into a service boat both in this country and abroad.

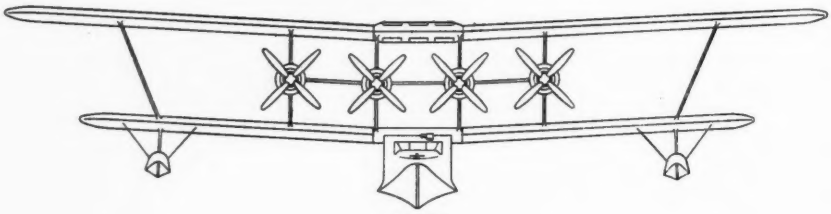
Future trend of development will, I am certain, be a complete divergence of the two types. The Service boat appears, for various reasons, to be approaching a limiting size, whereas no limit is yet in sight for the civil boat, and each succeeding design either built or contemplated is appreciably greater in all-up weight than its predecessor.

The general problems relating to hull form, method of lateral stabilisation and aerodynamic characteristics are, of course, common for both types. Perhaps the main cause for the different treatment of the two types lies in the fact that,

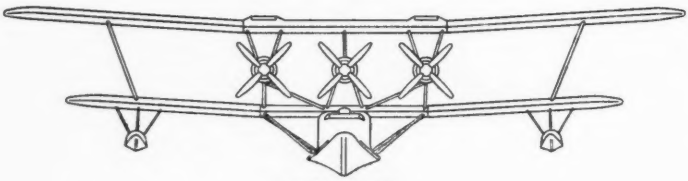
FIG 1



EMPIRE BOAT.



KENT.



CALCUTTA.

in general, the civil boat operates from selected harbours which are equipped with all the ground services essential for efficient and safe operation, whereas the Service boat will or may have to operate under widely varying conditions necessitating more consideration being given to its seaworthiness properties.

For the purposes of this paper, however, we are chiefly concerned with the development on the civil side.

Fig. 1 shows in front elevation the three boats which form the subject matter of this paper.

The " Calcutta " was the prototype of our civil boat design and was equipped with three engines, being followed later by the " Kent " which had four engines installed. Both of these types were biplanes and of very similar design, the " Kent " being actually modelled on the " Calcutta."

The " Empire " boat being a four-engined high wing monoplane was a complete departure from the earlier types.

The boats were all constructed of metal, but with some differences in the materials employed. For example, the " Calcutta," with the exception of the covering surfaces, was built entirely of duralumin. The " Kent " was similar with the important difference that the planing bottom surface was of stainless steel. The " Empire " boat is built chiefly of Alclad to D.T.D. specification 275, although the spar extrusions are of R.R. 56 alloy. With the exception of the control surfaces, the wings and tail unit are also metal covered. It will probably be asked why a departure was made from the stainless steel bottom, which has given such excellent service on the " Kent." Frankly, I think that stainless steel is the ideal material to use for this purpose, but it would probably have involved us in an additional 300lbs. in weight, and with the excellent results now being obtained from Alclad there did not appear sufficient justification for the corresponding loss in pay load.

Table I gives the summary of the general characteristics, and there are two points in this table which call for some comment.

TABLE I.

General data.	" Calcutta."	" Kent."	" Empire " Boat.
Wing area, sq. ft.	1,815	2,640	1,500
Engine, b.h.p., maximum	1,605	2,332	3,180
Engine, b.h.p., normal	1,515	2,140	2,960
Wing loading, lbs./sq. ft.	12.4	12.3	27
Power loading, lbs./h.p., normal ...	14.9	15.2	13.7
Hull beam, ft.	10.0	11.25	10.0
Hull length, ft.	60.5	71.9	88.0
Year of construction	1928	1931	1936

The first relates to the wing loading. It will be noted that the wing loadings are approximately the same for both the " Calcutta " and " Kent," whereas the " Empire " boat, at the normal weight, has a wing loading of 27 lbs./sq. ft., which is more than double that of the earlier boats.

This point will be further discussed when the performances of the respective machines are being considered.

Secondly, I would like to call your attention to the beams of the respective boats. It will be noticed that the beam of the " Calcutta " is 10ft. and that of the " Kent " 11ft. 3in., these being proportional to the cube root of the respective all-up weights. For some time past it has been my conviction that it should be possible to build hulls with a much narrower beam than was our accepted practice, without incurring any appreciable loss in hydrodynamic efficiency. An extensive series of tank tests were put in hand and it was finally found possible to limit the beam of the " Empire " boat to 10ft. as against a beam of approximately 12ft. 3in. that would have been required on the earlier requirements.

The results obtained from the tank tests will be discussed later.

Again referring to the table, it will be noted that the engines of all three boats were built by the Bristol Aeroplane Co., and I should like to pay a tribute to this company for the valuable work that they have done in recent years in furthering the cause of the civil flying boat.

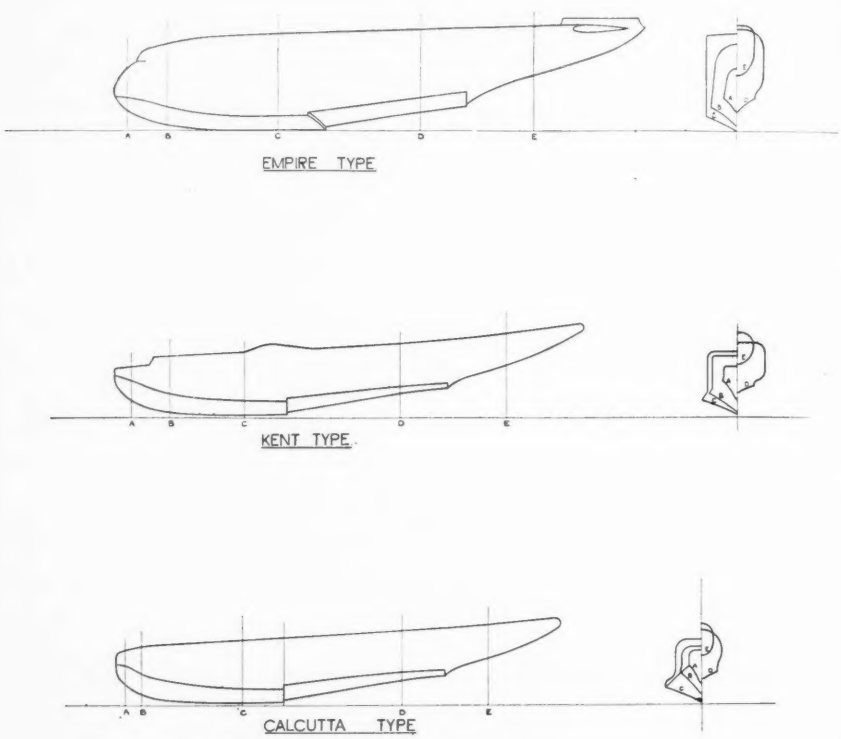
The " Calcutta " was equipped with three " Jupiter " IX engines, the " Kent " with four " Jupiter " X.F.B.M.'s, and the " Empire " boat with four " Pegasus " X.C.'s. An interesting point to observe is that the power loading of the " Empire " boat is about 11 per cent. better than that of the " Kent."

Fig. 2 has been prepared to illustrate the differences between the respective hulls and they have been drawn on the basis of a common weight in order that they are directly comparable.

The relative data are as follows:—

	A. "Calcutta."	B. "Kent."	C. "Empire" Boat.
Take-off speed (knots)	56	57	68
Lbs. of gross weight/inch of beam	187.5	240	338
Overall length/beam	6.05	6.39	8.8

The first point that arises from a study of the diagrams is the comparatively greater length of the " C " type hull. The overall length is, of course, governed by aerodynamic considerations and at the moment does not directly concern the



HULLS BASED ON SAME ALL UP WEIGHT

comparisons, but I do wish to draw your attention to the greatly increased depth of hull employed on the " C " type.

Two main reasons are responsible for this depth:—

(1) The cubic capacity required for accommodation of passengers, mail, baggage, etc.; and

(2) The necessity of providing adequate water clearance for the flaps and airscrews.

The lengths of the forebody planing surfaces are approximately the same for types " A " and " B," but type " C " has a longer forebody, found necessary on account of the beam reduction.

The decrease in the beam is distinctly shown in the sections and amounts to approximately 20 per cent.

FIG. 3.

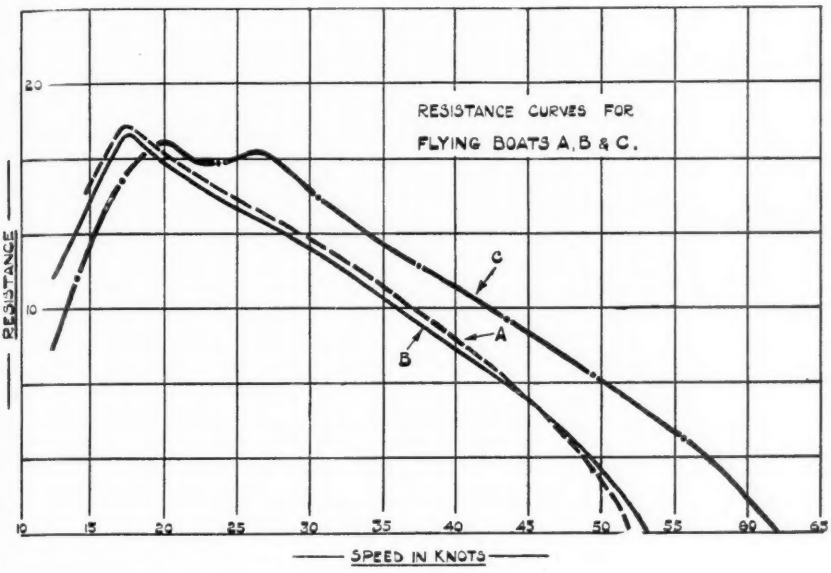

RESISTANCE CURVES FOR
FLYING BOATS A, B & C.
RESISTANCE
SPEED IN KNOTS
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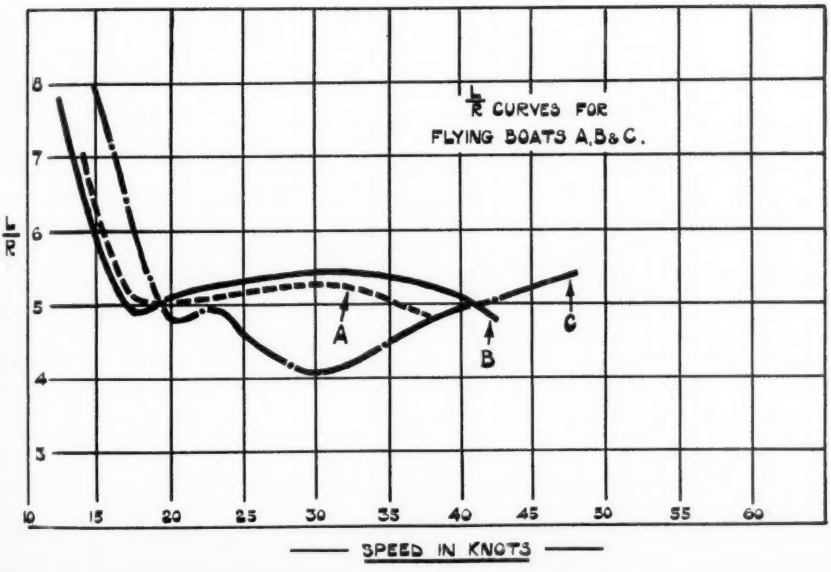
FIG. 4.


L/R CURVES FOR
FLYING BOATS A, B & C.
L/R
SPEED IN KNOTS
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60

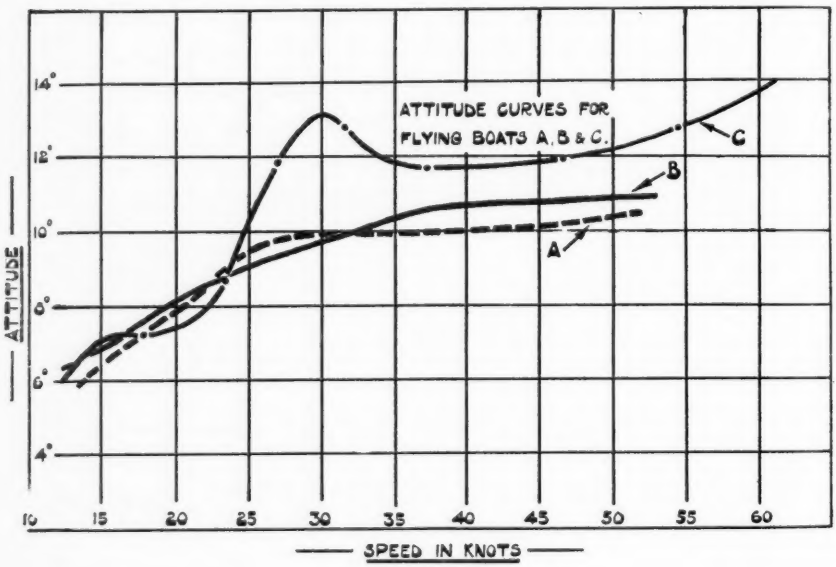
The afterbody planing bottom length of the " C " type boat, however, does not show the same disparity. This, again, was determined from the tank tests as it was desired to keep down this length to a minimum consistent with adequate longitudinal stability when planing.

The considerably higher wing loading, combined with the desirability of improving the aerodynamic shape of the hull resulted in some sacrifice being made in the water performances, and Fig. 3 shows the comparative resistance curves of the three hulls based on the same all-up weight.

The curves have not been plotted in non-dimensional form as it was desired to illustrate the higher water resistance of the " C " type hull at speeds above 20 knots which is due entirely to the narrower beam and higher take-off speed consequent upon the increased loading.

Fig. 4 shows the efficiency curves measured by the ratio load on the water divided by the resistance. The sacrifice in efficiency resulting from the reduced beam is clearly indicated, although it will be noted that this applies only to that

FIG. 5.



portion of the speed range between 25-40 knots. Above 40 knots the " C " type hull becomes more efficient than the other two.

The comparative running angles are shown on Fig. 5. Here again types " A " and " B " are very similar, whereas the natural running angle of type " C " is greater at speeds above 25 knots.

In considering these sets of curves it might be questioned as to why a hull with a basic increase in resistance could be accepted. Normally we should have considered this a retrograde step, but as we were able in this design to take advantage of two-pitch airscrews, the increase in thrust at take-off more than compensated for the increased water resistance.

In Fig. 6 an attempt has been made to estimate the respective thrust for the three boats, the thrusts being given as a function of the all-up weight.

If the thrust at 30 knots given by the airscrews of the " Calcutta " be compared with the thrust obtained from the airscrews of the " Empire " boat, it will

be seen that, whereas the " Calcutta " gives 1lb. of thrust for every 3.8lbs. of dead weight, the " Empire " boat gives 1lb. of thrust for every 3.05lbs. of weight. In the case of the " Kent " 1lb. of thrust is available for every 3.45lbs. of weight.

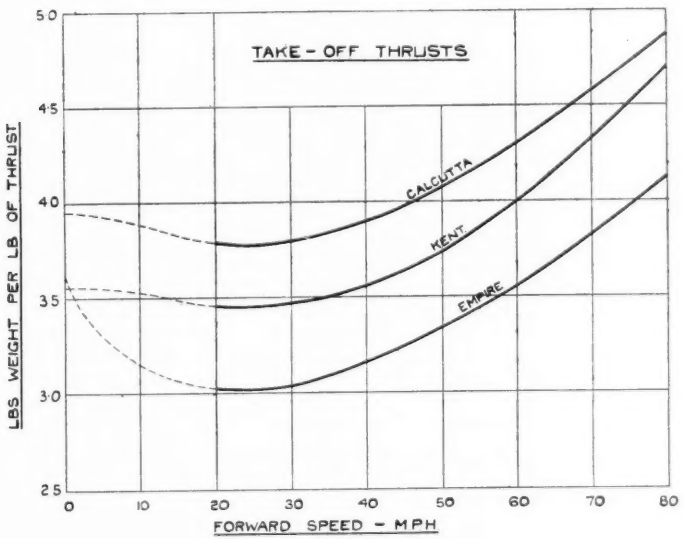
Modern developments in engines, giving, by the use of higher octane fuels, larger take-off powers, combined with the controllable pitch airscrew, have enabled us to take full advantage of the narrow beam and the high wing loadings without unduly sacrificing the take-off characteristics.

Opinions may be divergent as to what is considered a suitable take-off, but there is no doubt in my mind that for the type of boat we are considering (which has, of necessity, to operate from widely different waters) the run and time of take-off should be about 500-600 yards, and 20-25 secs. respectively.

For special routes operating from suitably selected harbours a longer take-off could be permitted and to this I will refer later.

It is interesting to compare the results obtained in practice for the three boats. On reference to Table II it will be seen that the take-off of the " Empire " boat is slightly worse than the " Calcutta," but distinctly better than that of the

FIG 6



" Kent." The take-off time of the " Empire " boat is that from the time of full throttle and with the hydraulic type of engine controls fitted it takes from 3-3½ secs. to obtain full throttle.

Therefore, in spite of the very considerable increase in wing loading the take-off time remains practically unaltered.

The take-off speed, however, is appreciably affected, increasing from 56 knots to 68 knots, and this has the effect of prolonging the run to take-off. As the take-off run is of more importance than the actual time taken, careful consideration would have to be given to the operating harbours when boats of even higher wing loadings than now being employed are under discussion.

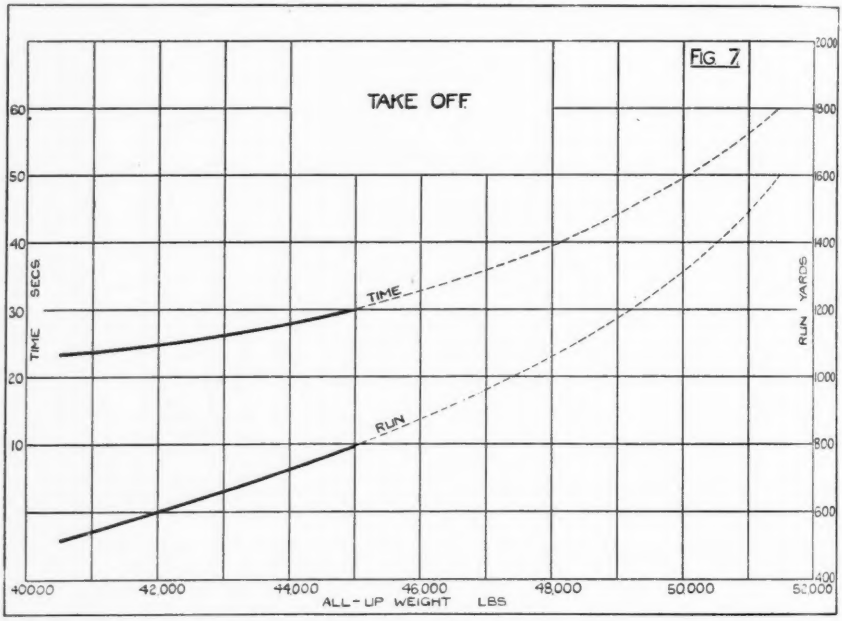
Two of the " Empire " boats are being placed in a special C. of A. category to enable flight tests to be carried out at an all-up weight of 45,000lbs., and tests have been made on the effect of the take-off at this increased weight.

These tests showed that the take-off time was increased to 30.5 secs. (again from full opening of the throttles) and the run to 795 yards, figures which are still reasonable and probably quite safe for operation from a large number of the available harbours.

The I.C.A.N. requirements state that the take-off from calm water must be less than 60 secs. with no wind.

From the tests which have been carried out at two different weights on the " Empire " boat, a fairly accurate prediction can be made of the limiting weight at which this type of boat can leave the water and still meet with I.C.A.N requirements.

Fig. 7 shows the relation between the take-off time and the all-up weight. If the assumptions made are reasonably correct the boat could be loaded up to 51,500lbs. before exceeding the limiting time.



The wing loading would then be 34.3 lbs./sq. ft., which is considerably higher than is used on any known aeroplane operating at the present time. Providing selected harbours can be used this fact opens up interesting possibilities for the future. It must be borne in mind that we have by no means reached the limits of available thrust as improvements will undoubtedly be made in the ground power of engines combined with a two-speed gear, and the static efficiency of the airscrews.

To what extent this improvement can be made it is difficult to surmise, but one can foresee that boats may be operating under their own power up to a wing loading of approximately 40 lbs./sq. ft.

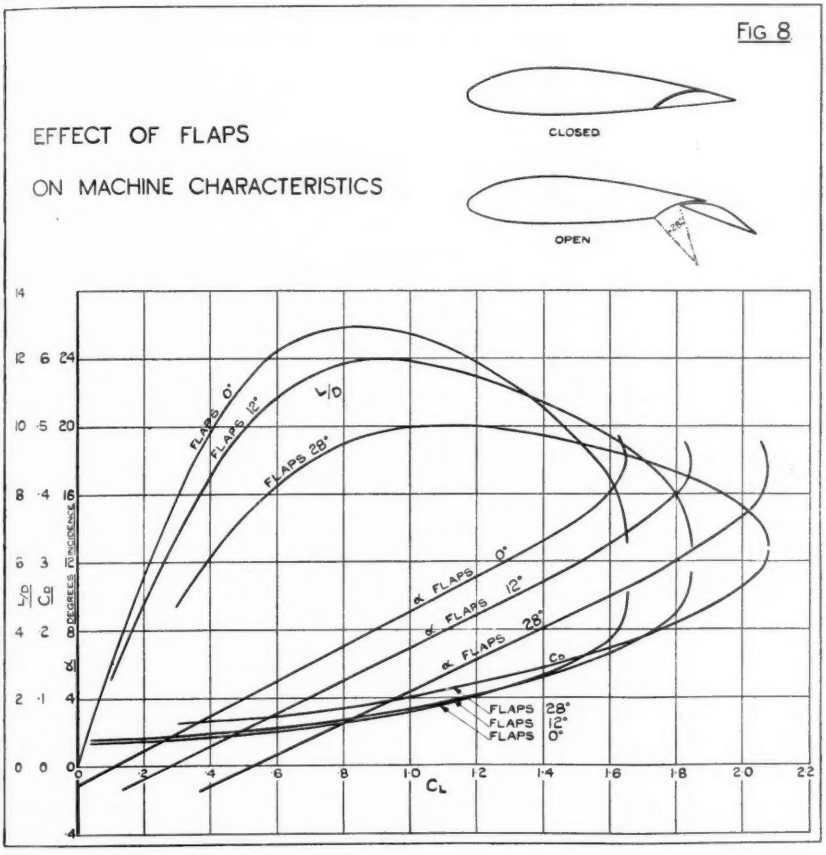
I would not advocate such loadings being used on small boats, but only for the development from the size of the " Empire " boat which may be contemplated in the future.

It is only fair to point out that the theoretical limiting weight shown on the curve may not be realised in actual practice as the water conditions caused by operating the boat in such an overloaded condition may somewhat limit the

weight. Complete tank tests would need to be carried out to establish this point and it would probably be found necessary to increase the beam slightly to avoid the hull becoming too dirty.

This analysis of the limiting take-off weight for the " Empire " boat more or less confirms my investigations into the same problem in 1927 when it was established, in my own point of view, that the limiting take-off weight is independent of wing loading.

Even so, the actual take-off of the " Empire " boat at weights exceeding the normal has exceeded our most optimistic estimates.



It is, of course, almost essential, when these high wing loadings are employed, to use some form of flap in order to assist the take-off.

As is well-known, several types of flap are now in common use and these can be roughly divided into two groups, viz., those having high and low drag respectively. In the particular case of the flying boat a steep angle of glide, when coming in to land, is not of vital importance and therefore it is better to fit a type of flap which as much as possible can be used for the take-off.

Until the design of the " Empire " boat was under consideration my experience with flaps had been extremely limited, and I did not know exactly their effect on the aerodynamic characteristics of the machine. My conclusions, therefore, were

that it probably would be better to design a flap which would appear to fulfil the conditions and to test it out in full-scale on a small aircraft. This led to the particular type adopted in the "Empire" boat, the prototype tests on which were carried out on the "Scion" by the Royal Aircraft Establishment.

In essence the flap is of segmental form which is let in flush at the trailing edge of the wing. This segment can be extended backwards and downwards as indicated in the right hand top corner of Fig. 8.

The flap is operated by rotating the segment in curved tracks, the net result of a rearward movement being an increase in the aerofoil chord and a flap effect at the trailing edge. Fig. 8 also gives the resulting increase in C_L and C_D over the range of movement.

In particular actual results are given for 0°, 12 and 28 degrees of rotation of the segment.

It will be appreciated that, as the wing has a straight taper, both in chord and thickness, the shape of the curved surface of the flap is conical and when rotated it therefore rotates about the axis of a cone.

Although, in addition to obtaining a reduction in landing speed, the flap was designed with the object of assisting the take-off, yet there are limitations to the extent to which this can be used.

The hull of the "Empire" boat, for example, has a natural running angle of approximately 9 degrees at the take-off speed, the angle being measured from the keel of the forebody as datum.

If the angle of incidence of the wings is, as in the case of the "Empire" boat, 3 degrees to the datum, which angle is largely determined by the attitude of the boat in cruising flight, then it is evident that, at the take-off, the angle of incidence to line of flight is about 12 degrees.

As the lift coefficient of the wings reaches a maximum at about 18 degrees it is obvious that full advantage cannot be taken of this value of C_L during take-off.

It follows that any flap device used to obtain an increase in the lift coefficient must not be accompanied by a serious increase in drag at this take-off angle of 12 degrees.

The results of a wind tunnel test on the "Empire" boat flap are shown on Fig. 8, from which it will be seen that the lift coefficient with 0 degrees of flap is 1.28 with 12 degrees of flap, the lift coefficient is 1.5 and with 28 degrees of flap the lift coefficient is 1.8.

The corresponding figures for the drag are 0 degrees of flap C_D=0.1125, 12 degrees of flap C_D=0.145, and for 28 degrees of flap C_D increases to 0.21. The figures given do not take into account the slipstream effect which would have considerable effect on both coefficients.

A fully comprehensive series of take-off tests with varying angles of flap have not been made, but from such tests as have been made it would appear that the boat takes off quickest with about 12 degrees of flap. Take-offs with 28 degrees of flap have proved to be longer than without any flap in operation.

On the other hand, the best take-off of the "Scion," when tested at Farnborough, was with the flaps fully extended, but the wings in the case had considerably more plan taper.

For landing full advantage can be taken of the flap and pilots invariably use the whole range available. In full-scale the reduction in the landing speed is of the order of 10-12 m.p.h., there being no change of trim or reduction in efficiency of the aileron control.

An interesting point regarding the lateral control was brought to notice by our test pilot, Mr. J. L. Parker.

If, when coming in to land, a wing drops from any cause and is accompanied by a turn in the direction of the down-going wing a small amount of throttle on either of the engines on that side immediately rights the machine, due to the slipstream effect on the flap and, at the same time, corrects the turn. This was

a point I had not appreciated, as this powerful addition to the lateral control on a multi-engined machine is very valuable at low forward speeds.

It will be instructive to review, briefly by a comparison of the relative performances, the extent of the progress made aerodynamically.

Table II has been compiled giving these performances as obtained from actual flight tests.

TABLE II.

Performance.	"Calcutta."	"Kent."	"Empire" Boat
Take-off time, secs.	23	26	24
Rate of climb, max. ft./min. ...	660	830	933
Ceiling, feet	13,000	19,500	20,000
Maximum speed, m.p.h.	123	137	200
Cruising speed, m.p.h.	94	105	164
Range, miles	650	450	800
Minimum flying speed, m.p.h. ...	60	60	71

The first point worthy of note is the minimum flying speed of the respective boats, this being in the case of the " Calcutta " and " Kent " 60 m.p.h., and in the case of the " Empire " boat 71 m.p.h. The higher minimum flying speed of the " Empire " boat is, of course, a natural sequence to the much heavier wing loading, although when one considers the actual difference in wing loading, this increase is relatively small.

The take-off speeds, given earlier in the paper, are higher than the minimum flying speeds, due to the fact, as explained before, that the maximum lift coefficient cannot be obtained during the take-off run.

In my opinion, given suitable stretches of water, there is no objection to the take-off speed being 20-30 m.p.h. greater than that of the " Empire " boat. This is particularly so in the case of boats built specifically for long range work, as the landing speed at the end of the journey is obviously much reduced owing to the consumption of the fuel.

It is not necessarily to be inferred from this that I would advocate a very much heavier wing loading on a boat of " Empire " boat size, but I do certainly think that wing loadings can increase with larger boats, and particularly so on long range boats. To my mind the insistence on low landing and take-off speeds which has characterised our specifications in the past has definitely retarded our progress and, in fact, had they still been insisted upon the " Empire " boat as such could not have been produced.

Referring again to Table II, it will be seen that the maximum speed of the " Empire " boat is 63 m.p.h. greater than that of the " Kent " and 82 m.p.h. above that of the " Calcutta." The engines of the " Calcutta " develop full power at sea level, whereas for the " Kent " and " Empire " boat the engines are moderately supercharged to 5,000 feet.

If the necessary correction be made to the speed of the " Calcutta " the performance of this boat and the " Kent " are approximately the same, which, from their similarity, is to be expected.

The improved performance of the " Empire " boat is due, primarily, as is evident, to the (1) aerodynamic cleanliness, (2) heavier wing loading, (3) slightly better power weight ratio, and (4) to more efficient airscrews.

In Fig. 9 curves are drawn showing the L/D plotted against C_L for both " Empire " boat and " Kent " which indicate, graphically, the extent of the improvement which has been achieved in the aerodynamic design.

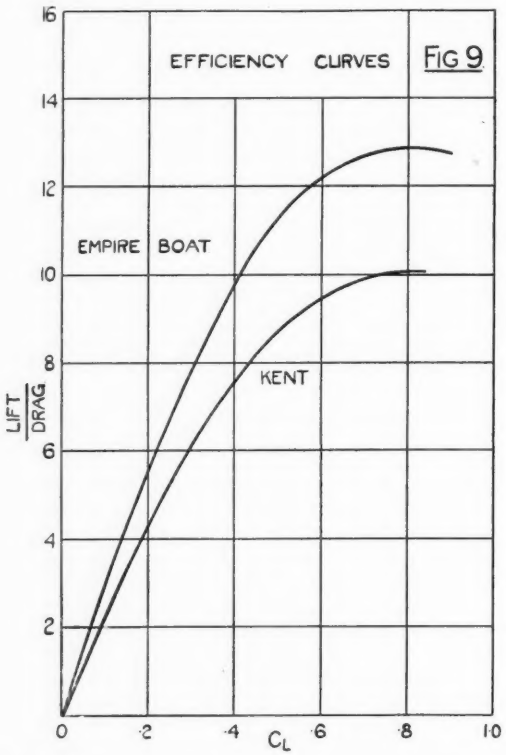
The part of these curves which is really important, as far as civil flying boats are concerned, is where the value of the lift coefficient is approximately 0.5.

From the curve it will be seen that the " Empire " boat is approximately 30 per cent. better than " Kent." (It is interesting to note that the lift coefficient at cruising speed at 5,000ft. is slightly smaller in the case of the " Empire " boat than in the case of " Kent " in spite of the increase in wing loading.)

Apart from the aerodynamic improvement, considerable advance has also been made in aero engine design, which has resulted, by the use of higher octane fuel, in an appreciable gain in fuel consumption.

Under cruising conditions this gain is at least 10 per cent. and it is probable that an additional 2-3 per cent. increase in efficiency is obtained from the metal controllable pitch airscrews.

This improvement is reflected in the ranges which can be obtained on the "Empire" boat. The standard boat was primarily designed for a range of 500 miles against a 40 m.p.h. headwind, although the actual tankage fitted is sufficient for a range of about 630 miles under the same condition. As mentioned earlier, two of the boats have been modified for the purpose of carrying out special long range flights and for this purpose they have been equipped with tanks of 2,320 gallons capacity.



It is not intended to use them for passenger carrying and therefore they will be in a stripped condition with provision only for carrying 1,000lbs. of mails.

On the assumption that the commencing weight is 45,000lbs., and carrying a crew of three with 1,000lbs. of mails, the ranges have been calculated at various cruising speeds against headwinds varying from 0 to 60 m.p.h. From Fig. 10 it will be seen that at a cruising speed of 160 m.p.h., this being in the vicinity of the normal cruising speed, the range, in still air, is approximately 3,300 statute miles, and against a 40 m.p.h. headwind the range is reduced to 2,470 miles.

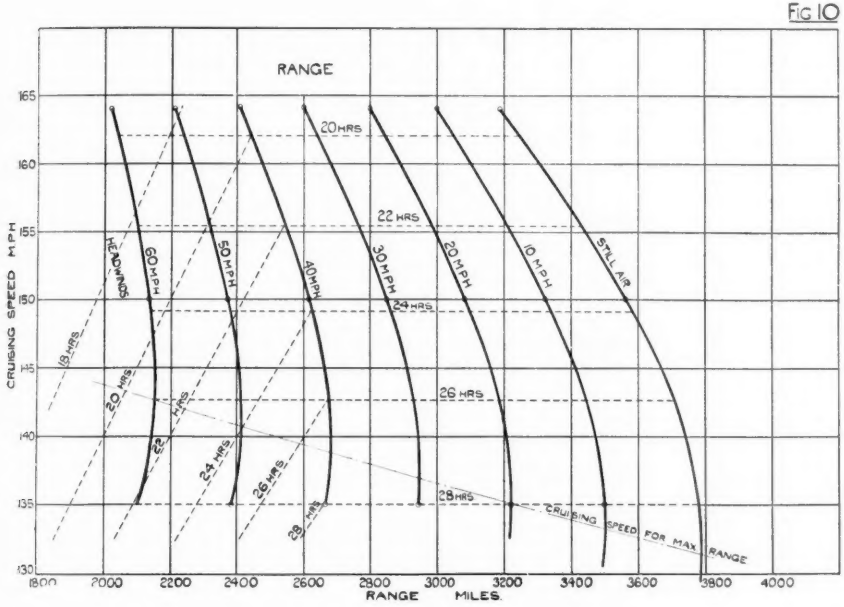
The limiting range is obtained when flying in the neighbourhood of the maximum L/D of the aeroplane, which in this particular case corresponds to

about 140 m.p.h., although it is to be noted that to obtain the minimum specific consumption at the lower power output the carburettors would need special tuning.

The curves have been based on an actual measured consumption at normal load and a cruising speed of 163 m.p.h., so the ranges shown for this particular speed are probably accurate.

The horizontal time lines crossing the range curves give the maximum ranges under various conditions, and the diagonal lines give the time required to fulfil a given journey against a 40 m.p.h. headwind at various cruising speeds, which emphasises the importance of high cruising speed when long ranges are contemplated.

Fig 10



Thus, for a range of 2,400 miles against a 40 m.p.h. headwind the flight takes 19.3 hours at a cruising speed of 164 m.p.h., but at 140 m.p.h. the time taken increases to 24 hours, the saving by cruising at the higher speed being 4.7 hours. The gain in time is about 24 per cent., but this would be at the expense of roughly 10 per cent. more fuel. For an actual service these two factors would need to be balanced against each other, but to my mind the higher speed and shorter time would, undoubtedly, prove the most economical in the end.

To obtain the ultimate range of the boat there would be no option but to fly at the most economical speed.

It is interesting to note how this range varies with headwinds of varying magnitude. In still air the best cruising speed for maximum range is about 131 m.p.h., but against a 60 m.p.h. headwind the best cruising speed is about 143 m.p.h., although in this latter case there is little to be gained by flying much below 155 m.p.h. With following winds the disparity between the ranges that can be obtained becomes greater for various cruising speeds, which means that on an organised route detailed charts would need to be prepared which would give the pilot the best cruising speed under any given set of conditions.

Referring again to Table II, there is one further point which is worthy of note regarding performance.

It will be seen that the cruising speed of the " Kent " is 105 m.p.h. and that of the " Empire " boat 164.

The petrol consumption of the " Kent," when first delivered, was approximately 92 gallons per hour for 105 m.p.h. The consumption of the " Empire " boat at normal weight is rather less than 125 g.p.h. for a cruising speed of 164 m.p.h.

It will, therefore, readily be seen that the " Kent " will fly 1.14 miles per gallon of petrol, and the " Empire " boat 1.31.

This, it will be appreciated, is a considerable advance when one bears in mind that the all-up weight of " Kent " is 32,000lbs. and the " Empire " boat 40,500lbs., or, looked at another way, the ton-miles per gallon for the " Kent " is 16.3, whereas for the " Empire " boat it is 23.7, an increase of 45 per cent.

TABLE III.

Item.	" Calcutta."	" Kent."	" Empire" Boat.
Weights—			
Power unit	3,433	5,437	7,496
Tankage	360	644	249
			1,018*
Structure	8,364	13,090	15,565
Equipment (including food and water)	1,663	1,780	3,012
Fuel	4,180	3,851	4,960
Payload and crew	4,500	7,698	8,200
	22,500 lbs.	32,500 lbs.	40,500 lbs.

* Luxury item.

Table III has been compiled to show the comparison between the sectional weights of the three boats. It is to be noted that, so far as the actual percentage of pay load is concerned, no material improvement has been made with the later design. Any saving in weight that has been achieved has been absorbed in providing more luxurious accommodation for the passengers. Actually it is difficult to make a strict comparison owing to the dissimilarity between the " Empire " boat and the earlier types.

For example, the power unit installation shows a higher percentage on the " Empire " boat. This is not only due to the higher power loading on this boat, but included in this weight are the metal controllable pitch airscrews. In the case of the earlier boats the airscrews were of wood. The " Empire " boat is equipped with electric starters, the total weight of which, including cable, is over three times as much as the gas starters fitted previously. Ring cowlings with controllable flaps are fitted to the " Empire " boat, such items of equipment not being in existence when the earlier boats were built.

The saving in weight in the petrol tanks is due to the substitution of light alloy in place of the tinned steel previously used, the tanks actually being produced for a weight of 0.3lbs. per gallon.

The structure percentage weight does not show much change, but in view of the very much greater cubic capacity proportionally of the " Empire " boat, the weight of the structure is relatively lighter in spite of the fact that practically the whole of the surfaces are metal covered.

An additional item of about 1,000lbs. is included in the structure which represents the weight of the additional luxury equipment fitted over and above that in the " Kent." The equipment weight shows a considerable increase and this is largely due to such items as automatic pilot, modern wireless equipment, including an auxiliary plant for operation of the W.T. when the main engines

cannot be used, and duplicated electrical and ventilation systems for day and night flying.

In the " Empire " boat equipment is also included an item of 530lbs. for food, water, etc., as against a similar item of 105lbs. for the " Kent."

It may be of interest to show the comparative weights of the standard and long range boats respectively.

TABLE IV.

" Caledonia."

Item.	Weight-lbs.
Power unit	7,590
Tankage	833
Structure	14,780
Equipment	1,447
Fuel and oil	18,750
Pay load and crew (3)	1,600
All-up weight	45,000

Table IV has been prepared showing the actual sectional weights of " Caledonia," the first of the long range boats.

Only the bare necessity of furnishings have been fitted and the equipment has been reduced to the minimum required for the particular duties. The power unit and tankage items are increased, due to the additional fuel carried, but a large reduction is shown in both structure and equipment. In the condition quoted the boat has a range of approximately 2,500 miles against a 40 m.p.h. headwind, cruising at 160 m.p.h. with a crew of three and carrying 1,000lbs. of useful load.

I have endeavoured so far, in this paper, to draw a fair and unbiased comparison between three successive stages of civil flying boat design, and I think it will be agreed that a reasonable measure of progress has been achieved. Will this progress continue in the future?

From the figures given it will be seen that during the last eight years the size of the flying boat, as governed by the specifications of the operating company, has increased in all-up weight from 22,500lbs. to 40,500lbs. Does it not seem a natural corollary that in the not far distant future flying boats will be designed of a size far exceeding those at present in existence? At the present time there are no problems to be solved in producing a boat of double the weight of the " Empire " boat which would have, in many respects, improved characteristics. Such a boat will be a necessity when consideration is being given to operating services over long stretches of water as, in my opinion, these must ultimately be carried out by flying boats, although a temporary period may exist when these services will be operated by landplanes.

One of the first essentials of a service like the trans-Atlantic crossing is the selection of suitable waterways, from which the boats will operate as, undoubtedly, higher wing loadings will be employed on boats for services of this type. From practical experience there does not appear to be any fundamental difficulty in taking off the water, given reasonably calm conditions, at speeds exceeding 100 m.p.h. In fact, with a properly designed hull operating from calm water, it is impossible to tell, from within the boat, the actual moment of leaving the water. I contend, therefore, that in calm water the vertical acceleration experienced is practically nil, although, of course, the water pressure on the planing bottom will probably increase with the wing loading.

With boats designed for long range work, the question of the landing speed does not arise as, at the end of the journey, the wing loading would be reduced to about 60 per cent. of that at the commencement.

For emergency landings, when flying at full load, it would be possible, by the fitting of jettison valves to similarly reduce the landing speed to normal.

These heavier wing loadings make for greater safety as such boats are less affected by bad weather and are able to withstand very severe conditions when at moorings.

The natural sequence to a high wing loading is an increased cruising speed, and as has been previously pointed out, a high cruising speed is essential if long ranges are to be carried out in reasonable time against a strong headwind.

Regarding this increase of wing loading with size, my own views are that for boats of about 80,000lbs. all-up weight the wing loading should be 34-35 lbs./sq. ft., whilst for boats of 160,000lbs. all-up weight the wing loading could safely be increased to over 40 lbs./sq. ft. In fact it is difficult to foresee what will be the ultimate limit of the wing loading.

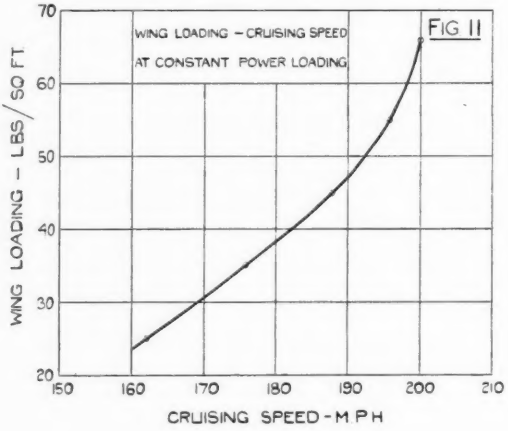


Fig. 11 has been prepared to illustrate the effect on the cruising speed of an increased wing loading.

The assumptions made are that the boats are similar aerodynamically and the power loading, altitude and the airscrew efficiency are constant.

The effect on the take-off due to the increased wing loading is not being considered here, as this is a separate question.

The curve for the constant power loading of 20, roughly represents the " Empire " boat, from which it is seen that by increasing the wing loading to approximately 45 lbs./sq. ft., the cruising speed could be increased to 188 m.p.h.

If the boats are kept geometrically similar with increasing size we shall automatically obtain this increased loading owing to the fact that the linear dimensions increase as the cube root and not as the square root of the all-up weight.

The question has often arisen as to why the wing tip floats have not been retracted on the " Empire " boat. This decision was made, primarily, because, up to the moment, we have been unable to produce a successful wing tip float of small enough dimensions to enable it to be successfully retracted in the particular wing being used. Such retraction will, undoubtedly, be achieved in the future, but it is most essential, in any scheme adopted, that the lateral stability at rest on the water or when turning in a strong wind is not sacrificed or prejudiced in any way. The retraction gear must also be 100 per cent. efficient as the loss of one boat in a fleet of twenty, due to ineffective wing tip floats, would more than outweigh the gain achieved by retracting the wing tip floats in the remainder.

Improvements have been made recently in the shape of afterbody of the planing bottom with the object of obtaining better aerodynamic efficiency, and there is not much doubt that, in future designs, some form of fairing for the front step will be evolved. By these means it will be possible to increase, still further, the aerodynamic efficiency of the structure. The spherical pilots coupe has already proved very successful, as not only does it conform to the general shape of the hull, but in heavy rain the windscreen is entirely clear of water.

The ducted oil coolers also appear to be extremely satisfactory.

The foregoing, in the main, has been a brief description of the progress made during the last eight years in the design of civil flying boats, and I think it will be generally agreed that a considerable advance has resulted in this comparatively short space of time.

I have no doubt that this rate of progress will continue and, in a few years' time, the boats discussed herein will be completely overshadowed.

In conclusion, I would like to express my appreciation to those who have helped me in the preparation of this paper, and in particular, my chief assistant designer, Mr. Lipscomb.

Discussion.

The President: The large attendance was evidence of the appreciation of the great importance of the subject which the author had dealt with in so interesting a way. Although the paper was entitled "Recent Progress in the Design of Civil Flying Boats," the author had spoken somewhat of the future, and it would be interesting if he could go a little further still. Stories had come from the other side of the Atlantic of very large boats indeed being contemplated, bigger even than the 75-ton flying boat to which the author referred. What did the author foresee in that respect? His own view was that progress in the past had been limited—indeed, controlled—by the engine power available. There was a practical limit in convenience to the number of engines one could have along the leading edge of these large boats, and on the corresponding amount of power, so that unless the engine power per unit, or per airscrew, went up substantially, it was difficult to increase the sizes faster than that particular rate prescribed. He also would like to know whether the author considered there was likely to be any marked change in aspect ratio of the wings, either upwards or downwards; and could he give his views as to where he thought the fuel was likely to be carried? The practice in different countries as to carrying the fuel in part of the hull seemed to be very variable.

The "Empire" flying boat was evidently going to provide an exceedingly comfortable means of travel, and it seemed that they were likely to have a very interesting contest in the future between different types of comfort in flying for civil purposes. On the one hand there would be the large comfortable boat capable of flying low down with safety, giving a view which was interesting, and also providing room to move about, whilst right at the other end of the scale the passengers would be put into a hermetically sealed container and automatically fed with air whilst the craft would fly at enormous speed, at an exceedingly high altitude where the view would be much less interesting. The public would have to choose, but he had his own impression as to which was most likely to be the more attractive. The author gave the ton-miles per gallon for the "Empire" flying boat as 23.7. A car weighing one ton would run this number of miles to the gallon so here was a case in which extremes met.

Major R. H. Mayo (*Fellow*): He would not attempt to go into any detail in regard to the paper, but there was one aspect he might be able to bring out to some extent. Whilst expressing his appreciation of the paper as a member of the Society, he also wished as a representative of Imperial Airways to express their very great appreciation of the author as a designer and as a producer of aircraft. He had had practical experience of all three types of flying boat designed by the

author, and each one of these aircraft had been extremely successful as a commercial type. He believed he was right in saying that each in its day had represented the best and most advanced standard of design. A great deal had been heard during the past few years of the inferiority of British aircraft design. They had been told they were years behind other nations and that it would take a very long time to make up the leeway. The author and Messrs. Short Bros., however, had demonstrated that that was not the case. The position had simply been that there had been periods of obsolescence which had to be gone through before new types could be produced. During such periods of obsolescence there must obviously be a lag and there would come a time in the life of any particular design when other designers would have advanced beyond that standard. But when the time came to take the next step forward British designers were ready and able to take that step, and there could not be a more convincing demonstration of that than the Empire flying boat.

Another aspect he wished to mention was a very significant one. In each of these three cases aircraft had been put into production without first building a prototype. In the case of the "Empire" boat, as most of them probably knew, an order for a very large number of these boats was placed before any construction whatever had started. He personally had had to shoulder a very considerable burden of responsibility in regard to the placing of that order but he had had no qualms whatever. There had been criticism both of Imperial Airways and to some extent of Short Bros., for embarking upon such an enormous programme without a prototype, but it would be agreed that the policy had been completely vindicated. That was a very important point because as time went on it became increasingly difficult to develop new types by means of prototypes. It took a very long time to produce a prototype and if that were done it meant putting back by something like two years the time when the type could come into service. Therefore, there was a very great advantage in omitting the prototype and going straight to production. But in order to do that it was necessary to be very sure of the designer and in the present case he could say they had been absolutely sure in that respect.

Major F. M. Green (*Fellow*): He wished to thank the author for two special reasons. The first was because the paper had been a model of conciseness. It contained a tremendous amount of matter of a solid character to think about and very little padding and it should serve as a model to all who wrote papers. His other reason for wishing to thank the author was rather personal. About three years ago he had the honour of reading a paper before the Society in which he discussed the economics of civil air transport, and from very general considerations he came to the conclusion that the sort of civil aircraft that was worth designing would be a good deal faster than was being designed at the moment. In fact, he came to the conclusion that the aeroplane which would be most useful would fly at from 130 to 150 miles per hour according to its landing speed. He was very severely taken to task at the time and was told that his conclusions were far too general and that speed had to be paid for. Moreover, he was told it was nonsense to think it would ever be possible to fly more economically faster than the speeds then adopted. The author, however, had made civil aircraft to fly at 164 miles an hour as a cruising speed. It was not possible to make a very exact comparison between two aeroplanes because there were always a number of new factors such as increase of luxury, engine power, etc., but he had tried to make a comparison in his own way. Taking the three aeroplanes described in the paper he had altered the pay load so that they all had the same range of 650 miles in still air. His criterion of the usefulness of an aeroplane was the percentage of the pay load expressed as a fraction multiplied by the cruising speed. That, of course, was the number of ton-miles that could usefully be done per hour. On that basis, the " Calcutta " had a figure of 19 at 94 miles an hour, the " Kent " had a figure of 29 at 105 miles an hour, and the " Empire " had a figure of 37

at 164 miles per hour. In other words, according to this method of reckoning, the "Empire" boat had 95 per cent. more revenue per ton of boat than the previous boat. A great deal of this improvement was undoubtedly due to improved technique, but the results were so overwhelmingly in favour of the faster boat that he felt he must thank the author for justifying his prediction of three years ago, and even bettering it.

Major R. E. PENNY (*Fellow*): There was only one civil flying boat firm in this country, yet without any competition, that firm had managed to keep in the forefront of flying boat development, and for that he wished to congratulate the lecturer.

One special point had struck him in connection with the future development, which seemed significant, although the lecturer had touched upon it very lightly—the question of take-off. Mr. Gouge had remarked that there was no reason why flying boats should not take off at speeds over 100 m.p.h. As he himself saw the position, however, the future flying boat would not take off at all under its own power, but would be designed for landing only. If that were so, there would be gained the advantage of smaller hull, less structure weight, and, aerodynamically, more efficiency. There was also an advantage as regards the engine. An aircraft with the assisted take-off, and therefore not requiring the maximum power output of the engine enables the compression ratio of the engine to be increased, and thus fuel consumption to be reduced. The present disadvantage of the compression ignition engine would be overcome and it seems likely that this type of engine will now come into its own for long distance traffic. He would like Mr. Gouge, if the subject was not too involved for the time at his disposal, to give them his views upon this aspect.

Mr. A. H. R. FEDDEN (*Fellow*): It must be a great satisfaction to the author to be able to speak of all this solid progress over a period of years. If he might be allowed to say so, he felt the greatness of the author was shown by the way in which he produced new designs, so to speak, "out of the hat" without any fuss or bother. Having been privileged to supply some of the equipment, he had always found that whatever they had to "break" to the author he always seemed to take without any concern. He well remembered having to go to the author about six weeks before the "Empire" flying boat was due to be ready. It had been found impossible to make the controllable cowling to function satisfactorily with the original servo mechanism, so the author just designed an alternative mechanical hand operated arrangement which proved satisfactory.

Dealing with the projected boat of the future, he said he took it that the author was waiting on what could be done as regards power. Thinking some 7 or 8 years ahead he felt there were tremendous difficulties in giving anything more than 1,700 h.p. continuous cruising power; that was for about 1.3 lb. per B.H.P. cruising. Would that suit the author as regards his biggest boat?

Turning to heavy oil, he asked the author's views as to what he was prepared to pay for it. Again, thinking in terms of six or seven years ahead, he did not see any possibility of giving more than 1,000 h.p. continuous cruising power. It was not possible to go as high in cruising power with the compression ignition engine as with the petrol engine, but, taking two engines, one petrol and the other compression ignition using heavy fuel, at 1,000 h.p. cruising power, he believed it would be possible to give the following figures; the petrol engine would burn 58 gallons an hour as against 43 gallons for the compression ignition engine, and the cost of fuel would be £10 17s. 0d. per hour for the petrol as against 25/- an hour for the heavy oil. The actual weights of the two engines would be about 1,600 lbs. for the petrol engine and about 2,100 lbs. for the heavy oil engine. In other words, the author would have to pay to the extent indicated for a gain in weight of about ½lb. per h.p., and it would be interesting to know whether he thought it was worth it and for what sort of range it would be worth it.

Mr. W. O. MANNING (*Fellow*): As an old worker in this field he must congratulate the author and his firm for the magnificent work they had done on the

" Empire " boat. One point he would like to raise was with regard to that rather indefinite question seaworthiness. What he was thinking of was alighting on or rising from really rough water. Normally, of course, this would not be necessary because he understood this boat was designed to operate from a fairly smooth harbour and alight in another harbour of the same type. It was always possible, of course, though very unlikely, that landings might have to be made elsewhere. As far as he could see, the slightly narrower profile of the hull of the " Empire " boat would be conducive to landing or getting off with rough water. Compared with the " Calcutta " and the " Kent " it seemed that the V shape of the bottom of the Empire boat was slightly sharper than that of the other boats and that also would be conducive to landing on rough water. On the other hand, the question of safety arose. When a boat was absolutely threshing through waves, load per square foot on the bottom would have some reference to the speed of the boat squared and the higher landing or taking off speeds would, in these circumstances, almost certainly produce very much heavier stresses to say nothing of the fact that the violent shocks to the bottom would not conduce to the comfort of the passengers.

Mr. J. A. C. MANSON: The only point he wished to discuss was the reference in the paper to the desirability of retracting wing tip floats, which had been impracticable owing to the size of float required. In the present formula for buoyancy of wing tip floats, the negative metacentric height was an important figure. If it were possible to lower the centre of gravity, say by carrying the fuel in the hull, the size of the wing tip float required by the formula would be reduced almost in proportion. On the other hand, the cross wind rolling moment might be more important than height of centre of gravity and no advantage would accrue in reducing that height. But in a paper read before the Society of Automotive Engineers at Los Angeles in October, 1936, the author—Mr. Schildhauer—stated that Pan-American Airways had found on the Martin Clippers that stubs instead of wing tip floats had several alleged advantages. In the first place, the stubs had reduced the over-all air drag although personally, he could hardly believe that. In the second place, the fuel was stored in the stubs and hull bottom which gave a low centre of gravity with enhanced stability and manœuvrability on the water. Thirdly, the stub provided an excellent platform for boarding, and finally, the stubs made refuelling much simpler and quicker. The author of the present paper must have considered stubs as an alternative to wing tip floats and it would be interesting to have his comments on the considerations he himself had just set out.

Mr. GARNER (*Fellow*): Whilst he appreciated the paper as other speakers had done, he felt a little disappointed that the author had not given a comparison between seaplanes and landplanes, and had not expressed his views as to which of the two types would ultimately be the most efficient, as the size increases. Mr. Gouge's views on this point would be most valuable. The seaplane had three great advantages over the landplane. In the first place, there was no need for a shock-absorbing undercarriage—water was a very good shock absorber. In the second place, water provided very good braking so that there was no need to carry brakes, and in the third place water provided a very cheap aerodrome. On the other hand there were these disadvantages: there was the necessity for lateral stabilisation; the water resistance was higher than the corresponding ground resistance for land planes; steps which slightly spoiled the form of the body were necessary; and there was the necessity for the hull and the wing to be in certain relationship in order that adequate airscrew clearance could be obtained. These were the main advantages and disadvantages, but personally he felt that as the sizes became larger, the disadvantages became less important, while the advantages remained. Certainly for large sizes there would be no need for such large stabilisers, and it was also well known that in the large sizes adequate airscrew clearance could easily be obtained without spoiling the arrangement of hull and wings. He would like to express the view that in sizes above 60,000 and 70,000

lbs. flying boats would be more efficient than landplanes, although alighting speeds would be a little higher. Such machines would be just as easy to handle and he believed they would be quite as safe as the corresponding landplanes.

In conclusion he would like to express his appreciation of the " Empire " boat, which had come up to all expectations, and was undoubtedly one of the finest flying boats produced by any country.

Mr. H. S. HALL (Imperial Airways, Ltd.) : He felt the "Empire" flying boat had spoken for itself, but he would take the opportunity of expressing in public the congratulations he had offered in private to the author and his colleagues on their magnificent achievement, not forgetting those in the shops who had worked so hard to turn that great conception into material form.

Lieut.-Col. HECKSTALL SMITH: Speaking as a yachtsman and without any experience of flying boats, he said he would like to know something about the seaworthiness of these flying boats. What was the amount of sea in which such a boat could be reasonably taken out and navigated and brought back again safely? It would be very interesting for the public to be able to know in what sort of weather one could expect to take a flying boat off the water. Once they were in the air, of course, they were all right. Around the coasts of Great Britain very different types of sea were experienced. The short steep type of sea was encountered around the south and south-west coasts but on the northern coast there was the long rolling sea. Therefore, it would be very interesting to know the class of sea in which these boats were capable of taking off and how they had improved in that respect in the space of time the author had been talking about, and whether with increasing tonnage these flying vessels would become more capable of being manœuvred in open coastal waters.

Mr. L. T. H. GREIG (Jersey Airways) : What was the limiting sea in which these boats would take off, because that would have a very big bearing upon the area of sheltered water required in relation to maximum permissible take-off and maximum permissible wing loading?

With regard to trans-Atlantic flying, the author had expressed the opinion that for various reasons the flying boat would ultimately supersede the land machine entirely, but he would like to ask one or two questions in that connection. One was with regard to noise. The President had already raised the question of aerodynamic noise at high speeds and if air transport was to be carried out at very high speeds, the question arose whether the bad shape of a hull and step might set up a degree of aerodynamic noise which would not be tolerable at very high speeds, if these speeds were to be of any material interest to civil aviation at all.

Another point was that the author seemed to envisage a maximum take-off run of about 1,600 yards. If one imagined a similar machine taking off from an aerodrome on a concrete surface, what would the run be by comparison? Surely there was very much less resistance to acceleration, and if that run could be brought down, by reason of a smooth surface such as concrete, to something of the order of 900 yards it would not be inconsistent with the use of a land aerodrome. In that case the only question that remained was the design of undercarriage for the aeroplane. Again, many people envisaged one machine carrying the whole of the passengers between, say, Great Britain and America. If the possible schedules were examined, assuming a flight time of 10 hours—which did not seem altogether impossible—he believed that a more frequent service of smaller machines would be more likely to pay than one very large machine with all its risks of incapacitation for a period of days from various kinds of minor mishaps. On the trans-Continental lines flying in America, frequency had paid whereas with certain other types of traffic which was encountered in Europe, size seemed to pay because people wished to travel at some particular time of the day. Had the author paid any attention to that point of view? Was it really necessary to go very much beyond the present passenger capacity, and might it

not be more economical to have 10 planes carrying 50 passengers each, than one machine carrying 500 passengers, assuming that the capacity required for the day was 500. In other words, was it better to carry all the passengers at one departure time instead of making it possible for people in various parts of the country to obtain more convenient connections?

Another point was flying altitude. Anyone who had flown extensively, especially in bad weather, over the sea at low altitude would agree there was not very much worth looking at, whereas higher up there were the clouds which were continually changing and which were never of the same appearance for long periods of time.

Dr. ROXBEE COX (*Fellow*): It was very interesting to note that the author seemed to visualise no limit to the size of the flying boat. At one time people talked about the limiting size of aircraft because they were thinking of a law that was now known to be fallacious. This law stated that because weight varied as the cube of the linear dimensions and lift as the square, a limit of size must rapidly be reached. Actually that law, such as it was, depended on the assumption of geometrical similarity both externally and internally and such similarity could not, of course, be assumed. It seemed to him, regarding the matter rather differently from the last speaker, that they had not yet necessarily reached the most economical size of flying boat. He was looking at the problem mainly from the point of view of minimum structure weight; and the increase in wing loading which the author prophesied tended to reduce the structure weight as a percentage of the all-up weight. Moreover, as bigger and bigger flying boats were built it was possible to take more weight out of the hull and put it into the wings. When that was done, the more the load was spread out across the span the smaller were the maximum wing bending moments. On this score therefore structure weight came down again. Also, with need for less hull space, the hull weight should be less. It seemed to him that there was in consequence considerable hope for the author's prophecy of truly enormous flying boats: they would probably build them many times greater than they had done so far. There was one point which interested him particularly; it was that if development followed the lines he had indicated, they tended more and more towards an ideal which had existed for a good many years—the flying wing. He thought the author might be interested in some work which Mr. Coombes and he did some time ago in this connection. They made a model of a "flying-boat—flying-wing"; it had no hull in the usual sense, but the wing was proportioned in a way designed to give it good qualities on the water. Tests in the R.A.E. tank showed that it had unusually good characteristics both from the point of view of taking off and landing, and was stable on the water without wing tip floats. In fact, in take-off, it appeared to be, on the whole, superior to the conventional form of boat. He was not suggesting that a flying boat should immediately be made on this principle! There were difficulties to be overcome. For instance, unless extra structure was introduced to carry the airscrews above the wing, or some form of retractable nacelle was used, it would not be possible to take off without the airscrews getting wet. Nevertheless, he mentioned the idea of the "hull-less" flying boat as a possible contribution to the future development of the flying boat and he would like to know whether the author thought it had any application in the ambitious designs which he envisaged for the future.

Mr. FAREY JONES: Few people had been given the satisfaction which must be the author's in having seen the evolution of three different types of aircraft and producing such a boat as the "Empire" flying boat. Although the author had virtually put the "Empire" boat as the third step, it seemed that he had something still better to come because he had said he conceived of no difficulties in flying boats having an all-up weight of twice the weight of the present "Empire" boats. Personally he was particularly interested in the author's view of what the "Empire" boat of the future, say, 80,000 or 100,000 lbs. all-up weight was going to be like. Was the author going to continue with petrol engines using very high

octane fuel, and if so, how many such engines would be required on a boat of 80,000 or 100,000 lbs. all-up weight?

In Table IV details were given of the "Caledonia," and it seemed to him that if designers had everything to be proud about, the manufacturers of engines had still more to be proud of in the marvellous engines they produced to make the manufacture of these aircraft possible. The author has referred to the enormous disparity between the weight of fuel and oil required and the pay load and crew. For the long range "Caledonia" of approximately 2,500 miles against a 40 miles an hour head wind, the weight of fuel and oil was 18,750 lbs., whilst the weight of the pay load and crew was 1,600 lbs., and he believed that 1,000 lbs. of that was the useful mail load. Would the author indicate whether the boat of the future with twice the all-up weight of the "Empire" would exactly double these figures from the operational point of view, or would the weight of fuel and oil be reduced in proportion to the increase in total all-up weight? That was the problem the operator had to solve because in developing the "Empire" boat of the future, a doubling of the all-up weight must come in the next five or six years, for if a bigger boat were built it would be built for one purpose and for one purpose only, cruising either the North and South Atlantic or the Pacifics, and the only way that even very big and experienced organisations like Imperial Airways would be tempted to go in for that type of experiment, was the possibility in the next five or ten years of reducing the total weight of fuel with a similar weight, if not an increasing weight, of payload.

Mr. S. Scott Hall (*Associate Fellow*): He called attention to a remark in the paper:—"The take off time of the Empire boat is that from the time of full throttle and with the hydraulic type of engine controls fitted, it takes from 3 to 3½ seconds to obtain full throttle." He suggested that the time taken to obtain full throttle, however, was simply a function of the way the pilot used the control. If 3 to 3½ seconds represented lag, it rather suggested there might be difficulty in a case of emergency when the pilot wanted to open up the engines suddenly. It might also introduce difficulty in the mooring-up operations when a responsive throttle control was essential.

Mr. Frank Radcliffe (*Associate Fellow*): After reading with the greatest interest Mr. Gouge's paper on Flying Boat Development, he was greatly impressed by the high order of efficiency achieved by his "Empire" flying boats when measured in terms of gross weight/tare weight.

By means of flaps, higher wing loadings, V.P. airscrews and clean form, the cube law has to a very marked extent been sidetracked, and it speaks well for his form of construction when one realises that his ratios are apparently as good as the best American.

It also seems reasonable to expect that this high ratio (approx. 2.0: 1) might be improved upon if future aircraft of a similar type were built, because development work should always result in a refinement of design with its consequent gain in structural efficiency.

With the use of four engines, the risk of a forced landing should be almost negligible and the slip-stream effect on take-off and landing must be very appreciable.

He would be interested to learn whether Mr. Gouge had done any vibratory tests on tail planes and fins to find out how these compare with those for smaller craft. This is a test which appears to be receiving attention in the U.S.A. for, according to a recent S.A.E. paper, in order to keep the rigidity of these fixed surfaces above the band of critical values possible for the control systems, or from the wings, it has been found necessary to increase the thickness—chord ratio and make them definitely stronger than minimum standards.

It would be appreciated by many, if Mr. Gouge could give any information on the weight of the wing system of his latest boats. Also, what would be the percentage cooling loss that should be allowed for in aircraft of this type?

Reply to the Discussion.

There has been a considerable number of points raised during the discussion and I hope to reply to as many of these as is possible.

The President raised the point of the very large boat and I quite agree that the development of these boats is largely a matter of obtaining suitable engines. The airscrew problem, also, may prove a little difficult as it is essential to keep down the tip speed under cruising conditions to avoid excessive noise and, at the same time, to obtain the maximum possible thrust at take-off.

I quite agree that it is desirable to limit the number of engines spaced out along the wing to a maximum of six.

As far as the design of the structure is concerned, I do not think there are many problems to be solved before undertaking the design of a boat of 75 tons all-up weight or even more.

Regarding the aspect ratio I believe in this being kept to about seven as the larger aspect ratio does assist in spacing out engines along the wing, and so far, we have not encountered any wing trouble on the " Empire " boat, which is probably due to the structural methods employed.

The question of the fuel stowage is a matter of opinion, but personally, I feel that with the petrol in the wings, the aeroplane has improved flying characteristics and is better from the point of view of the comfort of the passengers. On the other hand, with the fuel in the hull, the water characteristics are somewhat improved. With increasing ranges and wing loadings, we may, in the future, be forced to carry a considerable amount of fuel in the hull.

I must thank Major R. H. Mayo for his kind remarks about the boats generally, which recalls to me that one or two of the " Calcutta " class are still in service. Not long ago I suggested to Major Mayo that these boats might now be retired, but he had replied that Imperial Airways were very short of boats on the Mediterranean. However, I hope that this will soon be remedied.

It was true that Short Brothers had taken an order of very great magnitude for these boats, and perhaps in doing so, had involved themselves in a certain amount of risk. The risk taken, however, was not so great as appeared on the surface, as, whilst all the preliminaries connected with the placing of the order were being settled a half-scale model was built, from the results of which it was not found necessary to modify any feature of the " Empire " boat beyond increasing the trimming tab on the rudder.

With the rapid rate in progress of aeroplane design, one certainly has not time to build prototypes if it is desired that the operating aircraft be always up to date.

In connection with Major F. M. Green's comments on the increased cruising speed, this has come about largely because of the greatly increased wing loading and the cleanliness of the design. In comparison with the " Kent " the cruising horse power loading of the " Empire " boat is a little less, but not enough to influence much the relative cruising speeds. Of course, the two-pitch airscrews fitted have made possible the high wing loading employed.

The problem of the assisted take-off mentioned by Major R. E. Penny is an interesting one, but I think this is definitely a case where it would be necessary to build a prototype before proceeding with the construction of a quantity.

A different field, entirely, is opened up when consideration is given to an assisted take-off.

It is quite true that the performance for a given pay load would increase and the operating cost of the boats themselves would be reduced. One must, however, weigh up these advantages with the initial cost and upkeep of the catapults, and if these are installed on special ships this cost may be considerable. Personally, I see no difficulty in the operation of large boats at take-off speeds of 100 to 120 m.p.h., providing suitable waterways are available. Several speakers have raised the point as to what I would consider to be a suitable sea from which these boats could operate. The best illustration that I can give of this is the stretch of water at the mouth of the Medway between Gillingham and Port Victoria.

Boats could operate from this under any conditions, except fog, without fear of sustaining any damage to the structure. I would not advocate operating under conditions that would be experienced in the North Sea, as it is impossible to make the structure sufficiently rigid to withstand high velocities in rough seas, and I do not see how this can be expected.

The foregoing remarks answer Mr. W. O. Manning's observations on seaworthiness. Actually, I believe that the " Empire " boat is more seaworthy than her predecessors. Under normal conditions the take-off is certain and extremely clean, and I have no reason to suppose that the boat would not take-off or land on a comparatively rough sea, but there is always the possibility of damage occurring to the tail plane, main planes or airscrews.

Mr. Manning also mentioned the shape of the hull, and he is correct in stating that the " vee " of the " Empire " boat is slightly less than with the other two boats. The narrower beam does make the boat easier to take-off and land. The stresses on the bottom are proportional to the size of the hull which might lead to trouble in rough water in the case of the flying wing.

Mr. J. A. C. Manson raised the interesting point of the possibility of wing tip float retraction. I think all are agreed that this would be desirable in the interests of performance.

With increasing wing loadings and the necessity of providing adequate lateral stability, the problem is not easy, but one which, no doubt, will be satisfactorily solved. Placing the fuel in the hull, will, by the lowering of the centre of gravity, reduce the size of the floats necessary for a given stability, but there would be objections to this.

The criterion for wing tip floats and lateral stabilisation generally is turning in a side wind and this is probably not much affected by C.G. position. Wing loading, however, is very important, and as this increases it may be possible to reduce the wing tip float size so that they can be readily retractable.

Mr. Manson also refers to stub planes as a method of stabilisation. This, of course, is an old point of controversy, and I think it is difficult to give a definite answer as to which is the better arrangement. Personally, I believe that on the score of both aerodynamic and hydrodynamic efficiency, the wing tip float has the advantage, and from my experience, I prefer to retain this method. In the case of the " Empire " boat the magnitude of the order precluded too many experimental features being incorporated and this was the main reason why stub planes were not considered.

Mr. H. M. Garner said that he wished the paper had contained some comparisons with contemporary landplanes and as I had expected that such a question would be asked I had come prepared with a reply. Comparisons have been made between the D.C.2, the Fokker F.36 and the " Empire " boat by Mr. E. T. Jones of the Experimental Establishment, Felixstowe. I had no knowledge of the existence of this comparison until shortly before the date of the meeting.

The figures indicate that the " Empire " boat compares very favourably with both of these aeroplanes. The ratio of empty to loaded weight was a little better for the " Empire " boat than for the Douglas and about the same as for the Fokker, whilst the maximum speed was a little faster than the Fokker and slightly slower than the Douglas. It can be stated generally, therefore, that the flying boat of to-day is little, if any, inferior either with regard to the structural weight or performance to the corresponding landplane, and as size increases, I should expect the flying boat to become the more efficient.

Perhaps the chief difficulty with the landplane is to provide a suitable retractable undercarriage, and at the moment, I cannot visualise a simple and clean design for aeroplanes over about 50,000 lbs. in weight.

I much appreciate Mr. H. L. Hall's kind references to the workmen and others who have been concerned in the production of the " Empire " boat.

Regarding Lieut.-Col. Heckstall Smith's remarks regarding the class of sea in which the boats could operate, I have mentioned earlier my views on this matter

but more will be known on this point after the boats have been in service for some time, as during their period of service, many different types of seas will be encountered.

Actually as their size increases so will flying boats possess a greater degree of seaworthiness.

In my foregoing remarks I have also replied to Mr. L. T. H. Greig's question regarding the limiting sea in which boats could operate and I cannot too strongly emphasise the desirability of choosing sheltered water for this purpose. Regarding his query on noise, I have not heard the theory advanced before that the shape of the hull can influence the noise to any great degree. Personally, I should say that the source of any unpleasant noise is the airscrew, and if the cruising tip speed be kept down to reasonable limits the noise generated by hull shape can be neglected. Incidentally the noise level of the " Empire " boat is quite low in spite of the airscrew tip speed being in the neighbourhood of 770 ft. per sec.

I agree with Mr. Greig that the run to take off on a concrete runway of a landplane of a corresponding size would be considerably less than for a boat, and would probably be less than the 900 yards that he quoted.

A concrete aerodrome designed to suit all directions of the wind would be rather costly, and one would be limited to this particular aerodrome, whereas, with a boat there is unlimited scope for landing in emergency and a certain amount of choice for take-offs if required by any particular set of circumstances. I think too that passengers as a whole, would prefer that additional feeling of security that would be felt in a boat when operating over large expanses of water.

Mr. Greig also asks whether it would not be preferable to operate with smaller aeroplanes and more frequently. Personally I should say no, mainly because if one is considering flights of a duration about ten hours or more, passengers' comfort is of primary importance. My limited experience in the design of civil aeroplanes would indicate that the accommodation should be of the highest possible order, and in fact, quite as important as speed. This I believe can only be achieved in the large aeroplane. The question is really one for operating companies and when we do approach the stage of considering whether one machine shall carry 500 passengers or ten machines 50 passengers, the whole circumstances including operating costs will need to be thoroughly investigated. I would say though, that I should prefer one aeroplane carrying 50 passengers to ten aeroplanes carrying five passengers for durations of the order of ten hours.

I agree that other things being equal, it is preferable to fly at reasonably high altitudes especially with bad weather conditions.

In reply to Dr. Roxbee Cox, I have read the paper which he and Mr. Coombes had prepared relative to the flying wing, and I was very interested in their results and conclusions. If, however, Messrs. Imperial Airways, or any other operating company desired say six boats of an all-up weight of about 80,000 lbs., I should certainly not make it in the form of a flying wing. Nevertheless, I have a great respect for Dr. Cox's contribution to the problem, and have no doubt that if an experimental aeroplane could be built the results obtained would more or less bear out his conclusions.

I wish to take this opportunity of expressing my appreciation of thé help given to me by Mr. A. H. R. Fedden and his staff for their co-operation in the design of the engine installation, and at the same time, to congratulate him personally on his achievement in producing such excellent engines.

He asks whether a cruising horse power of 1,700 per engine would meet with my requirements for a future boat. There is no doubt that such an engine would keep our needs supplied for a considerable time to come. Four of these engines would enable a boat of from 55 to 60 tons all-up weight to be constructed, and it is possible that six of such engines could be employed enabling the weight to be increased to about 90 tons. If, therefore, Mr. Fedden can promise such engines within the next seven or eight years I should be quite satisfied.

With regard to the heavy oil engine, this is I think, more a matter for the operator than the designer, as the points that need consideration are chiefly within the operator's sphere. In my opinion, when long ranges are being contemplated, the C.I. engine, apart from other aspects, has an advantage in that less bulk of fuel is required, a point which is now assuming some importance.

For boats with an unassisted take-off, the engine conditions during take-off are vital, and if the C.I. engine is to be seriously considered, the take-off characteristics of the two types of engine should be comparable.

Taking into account the large amount of development work necessary with the consequent amount of time and cost involved, it would appear that a lead is required from official quarters as neither the engine builder, constructor nor operator is in a position to undertake the sponsoring of this development.

Mr. Farey Jones was interested in the type of engines that would be used for the 80,000 lbs. development from the " Empire " boat. The engines mentioned by Mr. Fedden would suit admirably, as four engines each of a cruising power of 1,600 b.h.p. would give the 100,000 lb. boat a better performance than is obtained with the " Empire " boat. Regarding the fuel question the advantage is slightly in favour of employing the C.I. engine for ranges similar to the Atlantic crossing, providing that adequate power and r.p.m. are available for take-off. At present the petrol engine appears to have an advantage in this representation, but this may not hold for much longer.

Mr. Jones also asked how the ratio of useful load to all-up weight would vary with increasing size.

First of all, it must be borne in mind that the " Empire " boat was designed specifically for a range of the order of 500 miles against a 40 m.p.h. headwind with ample accommodation for the full complement of passengers, baggage, mail, etc. This results in a hull size considerably in excess of what would be required for a trans-Atlantic service. In other words, the " Caledonia " hull is considerably oversized for the load that can be carried for the range quoted and therefore too much stress should not be placed on the figures when long ranges are being considered.

Actually, for a boat double the weight of the " Empire " boat the load that could be carried would be considerably more than the direct ratio of the load quoted for the " Caledonia." In all probability the boat would be geometrically similar, resulting in the beam increasing as the cube root of the respective all-up weights, which means that the area would increase more slowly than the weights. The resulting high wing loading would give a smaller relative size of boat and a higher cruising speed for the same cruising power/weight ratio, which would be reflected in the pay load that could be carried.

Dealing with Mr. Scott-Hall's comments regarding the time required to obtain full throttle, this is due entirely to the fact that a hydraulic system is employed. With such a system it is impossible to obtain instantaneous opening of the throttles owing to the necessity of transmitting the pilot's effort through a long length of oil piping. This has not been found to be a great disadvantage in the normal operation of the " Empire " boat and I should imagine that the gradual opening of the throttle would impose less severe conditions on the engines.

In answer to Mr. F. Radcliffe, no vibratory tests were carried out either on the tail plane or fins. The design of these components was based on certain minimum standards of depth at root to span which would appear to have resulted in them being quite free from the trouble mentioned. The weight of the wing system including centre section flaps, ailerons, fillets, platforms, tank mountings and miscellaneous fittings in the wings is approximately 3.9 lbs./sq. ft. based on the nett area.

The 611th Lecture read before the Royal Aeronautical Society since its foundation, January 12th, 1866

PROCEEDINGS.

A meeting of the Royal Aeronautical Society was held at the Royal Society of Arts, John Street, Adelphi, London, on Thursday, November 19th, 1936. In the chair: The President, Mr. H. E. Wimperis, C.B., C.B.E., M.A., F.R.Ae.S.

The CHAIRMAN: The lecturer that evening was Squadron Leader Nigel Norman and he was going to talk about aerodrome design. From a little conversation he had had with the lecturer already he was sure they were going to have a very interesting and profitable evening. Squadron Leader Norman was at Cambridge where he took an engineering degree and he was afterwards connected with railway organisation for six years, which was a very fine basis for engineering knowledge. Then he served in the War in the Royal Garrison Artillery and the Royal Engineers and he learned to fly eleven years ago. He was now Chairman of Airwork, Ltd., which looked after, if it did not own, the Heston Airport, and he was also Chairman of the Aviation Committee of the London Chamber of Commerce.

AERODROME DESIGN.

By Squadron Leader NIGEL NORMAN, F.R.Ae.S.

FOREWORD.

The present paper is confined to matters concerned with the requirements for landing and take-off of aircraft at land aerodromes, that is to the landing area.

In the selection of sites the questions that arise are size and over-all gradients. In development of a selected site account must be taken of directions of landing, dimensions of flightways or runways, local gradients or undulations, nature of surface. Finally, to ensure safety of flight the site must be protected by zoning.

The subsequent problems of detailed layout, of civil engineering in construction, of control and equipment, and of design of administrative and terminal buildings, though susceptible of more popular treatment, come later in sequence. My first more detailed study is therefore devoted to what may be termed the aircraft's point of view as to what it would like in order to bring in and take out its load in the most economical manner.

SIZE OF LANDING AREA.

It is common knowledge that there has been recently a trend towards larger aerodromes. In 1932 I myself referred in a paper for the Society to the generous planning at that time adopted in the United States, where I noted areas such as 640 and 947 acres reserved for major airport sites. Since then much has happened. The Air Ministry has laid down that where regular air traffic is anticipated it is desirable to provide considerably more than the minimum required to obtain the first category of license and what is termed the Air Ministry Standard Airport has come into being, described in the following words:—

> " It is envisaged that in future sites intended for development as municipal aerodromes for use by heavy airline traffic should preferably conform at least to a size affording in three directions runways of 1,000 yards in length

and 200 yards in width, and in the fourth direction 1,300 yards in length and 400 yards in width. These four directions should intersect at angles of 45°."*

It is appreciated, however, that at certain points a special class of airport may be required, and there are indications of the dimensions that may become accepted for such cases. At Berlin the new Tempelhof is planned as an ellipse with principal axes 2,400 and 1,700 yards. A similar airport 2,200 yards by 1,950 yards is planned at Rome. It is understood that at Paris, while the final plan is not yet decided, runs of from 2½ to 3 km. are proposed. At Frankfort, perhaps the centre point of Europe, runs of 2,400 yards and 1,700 yards have been provided for. At Amsterdam an oblong area 1,650 yards by 1,250 yards is to be prepared. While it is hard to get exact information as to such plans as the above there is no question as to what they indicate. My own views of what should be allowed at a metropolitan airport are illustrated by the layout recently proposed for a major Heston in which runs of from 2,000 yards to 2,260 yards were provided in the four main directions.

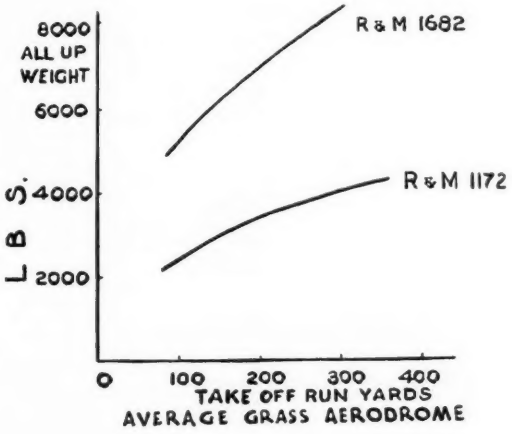


FIG 1

It is hard to say what factor will ultimately determine the size of major airports. So far as landing is concerned it may be the need for a big margin for error for landings in bad visibility. The take-off problem is being tackled from many directions. Mechanically assisted take-offs by catapult or accelerator may greatly reduce the space required. It would, however, appear that such systems will become increasingly difficult to operate as aircraft increase in size and weight. We must be prepared for land aircraft up to 100 tons in weight and 300ft. in span. Air fuelling offers another alternative, but the large aerodrome, already required for fog-landing, seems the simplest of all methods of increasing the economy of air transport operation.

Some idea of the increase in pay load to be obtained by lengthening take-off run is obtained from R. and M. 1172 and R. and M. 1682, where the ratio of increase in run to increase in all up weight is given by $X/X_0 = (W/W_0)^{2\cdot33}$. The results are plotted in Fig. 1.

Unfortunately the tests referred to were carried out with an aircraft of military type and old design using fixed pitch propeller. It appears that the available

* Note: These dimensions are confirmed in the recommendation of the Maybury Report recently published.

disposable load was doubled for an increase of run from 200 yards to 270 yards. I have obtained some calculated figures for a hypothetical case of a modern transport with wing loading of approximately 30lbs./sq. ft. For a range of 1,000 miles the pay load is increased by 60 per cent. by increasing the take-off run from 560 yards to 750 yards.

The use of these larger take-off runs will, of course, involve an alteration of the present international requirements for airworthiness. But the 56ft. screen has already been pushed back once from 560 yards to 656 yards and I think the air line accountants will soon insist upon its being pushed back even further. This tendency is recognised in a recent addition to the airworthiness requirements for civil aircraft in which a relaxation of take-off and loading requirements for long range aircraft is permitted at selected aerodromes provided that the aircraft has a range of at least 930 miles, is capable of level flight at 3,280 feet with one engine stopped (two if more than four are fitted) and is equipped with means of jettisoning fuel in flight.

Effect of Altitude and Temperatures.

Where an airport site lies considerably above sea level or where exceptional sun temperatures are experienced, the take-off and landing runs of aircraft are

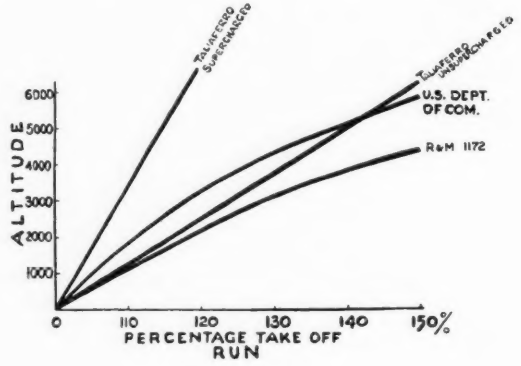


FIG 2

increased and the size of the runways should be proportionally greater. Cases may often occur where both these influences are at work, so that to ensure a normal margin of safety it is desirable to correct for them independently.

Various factors calculated for the purpose of correcting for altitude above sea level are given in Fig. 2, the sources being R. and M. No. 1172, U.S. Department of Commerce, Bulletin No. 2, and a recent article by Mr. A. P. Taliaferro, airport consultant, published in America. It is generally emphasised that such theoretically calculated factors should, wherever possible, be checked by full-scale experiment.

Fig. 3 gives factors for temperature ignoring the effect of air density upon engine power. In any particular case the resultant factor may be obtained by multiplying the sea level take-off run by both these factors. For example, at a height of 3,000 feet and a temperature of 150°F. the increase in take-off run required is 48 per cent. if the altitude curve from R. and M. 1172 is used, or 41 per cent. if U.S. Dept. of Commerce's curve is used.

Although the effect of altitude and temperature is perfectly appreciated by aircraft manufacturers and most operators, I have come across several instances of its being ignored by those responsible for aerodrome construction.

GRADIENTS.

We must note that it is usually very much harder to find an absolutely level site than to find a large one. The Air Ministry limit for gradient for licensing purposes is 1 : 50 with local undulations up to 1 : 40. There are rumours that this requirement may be stiffened up in the case of main airports.

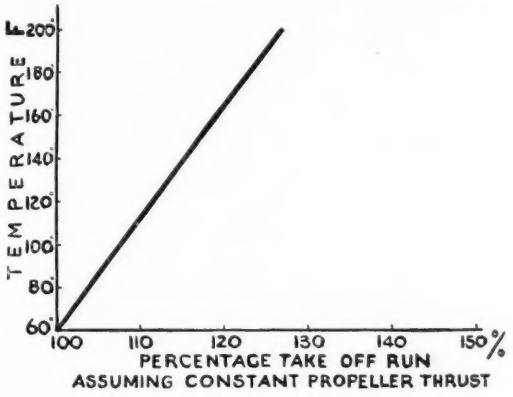


FIG 3

In practice an even continuous gradient is rare and it is usually necessary to level a site to avoid gradients of short extent, both up and down. Moreover, to provide a suitable level field it is desirable to avoid immediate changes of limit gradient, but to arrange for a gradual change from up to down and from either to level. In the case of the new Manchester and Birmingham airports a limit gradient of 1 : 60 was decided upon, but in the specification for contract for the latter the degree of levelling required was defined in terms of a maximum radius of curvature in the vertical plane of 9,000 feet. By such a definition a contour is obtained offering the minimum reaction to an aircraft running over it. On most sites it is not necessary to state that the maximum inclination to the horizontal of any tangent to the surface must not exceed the limit gradient.

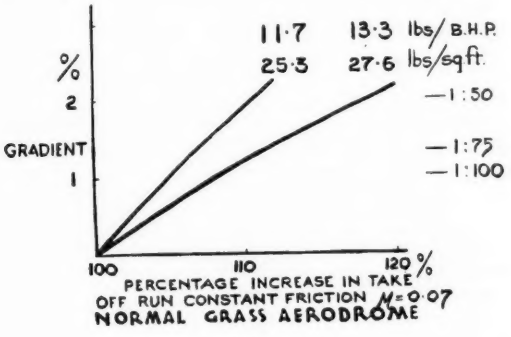


FIG 4

The effect of gradients of the order of 1 : 60 upon braking is not sufficient to be of importance, while the variation in glide path due to varying conditions of approach is so great in comparison that the effect of gradients at the moment of landing impact may be ignored.

Fig. 4 shows the calculated effect of steady up gradients upon the take-off runs of two types of commercial aircraft, one a light passenger aircraft of 6,500lbs. all-up weight, the other a large transport of 32,000lbs. all-up weight.

DIRECTION OF LANDING.

While for licensing purposes the Air Ministry take the length of run effective in all directions, the foreword to Pamphlet 55 already referred to indicates that the runs available in four main directions (eight directions of take-off and of landing) mutually inclined at 45° may be regarded as the criterion of efficiency of the aerodrome to serve regular commercial traffic. There are many aerodromes in use abroad where landing is confined to runways. A plan embodying four runways is regarded as the ideal, but in some cases only two runways at right angles are surfaced, while airport plans embodying three runways inclined at 60° have been suggested as adequate. Emergency landing grounds consisting of a single strip only are provided along many sections of main air routes. Conventional arrangements of four and three runways are shown in Fig. 5.

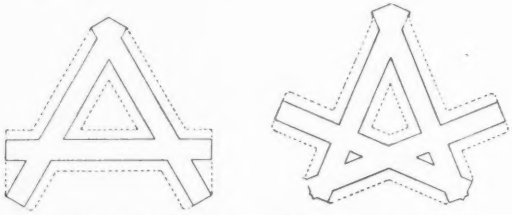


FIG 5

On runway aerodromes landings will often have to be made with the aircraft pointing "out of wind," a condition naturally disliked by pilots. The degree to which landing across wind can be made without risk of damage to the aircraft governs the number of runways it is necessary to provide, and thus greatly influences the cost of a runway aerodrome.

For small aeroplanes a technique has long been in use by which the pilot when landing across wind makes his aircraft sideslip into wind until the actual moment of touching, so that the landing is finally made without stressing the undercarriage abnormally, but this procedure is not practicable for large and heavily loaded aircraft.

The pilot approaching a runway in a side wind will therefore bring his machine in in a normal attitude. Its track over the ground will be along the axis of the runway, but it will be pointing in a direction inclined to windward by an angle θ depending on the wind direction and the relative speed of the wind and the aircraft. Its speed over the ground V_g will depend similarly upon the speed V_w, and the angle ψ of the wind to the runway. This condition is illustrated by Fig. 6.

At the moment of touching the aircraft wheels will be aligned at this angle θ to the direction of motion of the machine. If we ignore the inertia of the wheels and the friction of the bearings, the reaction upon the machine will be in a direction parallel to the axles. The magnitude of this reaction which we may call apparent drift will vary as $V_g \sin \theta$.

What happens next depends upon many things; the degree of skid of the tyres on the runway; the position of the centre of gravity of the machine relative to the wheels; the inertia of the machine about the centre of gravity; the steerability of the aircraft. The analysis of this period is a subject for separate study.

If, however, the aircraft continues on its way down the runway, as in fact it does, this reaction will have been overcome, partly by the pilot perhaps, but mostly by the aircraft designer. In this connection it is interesting to note that

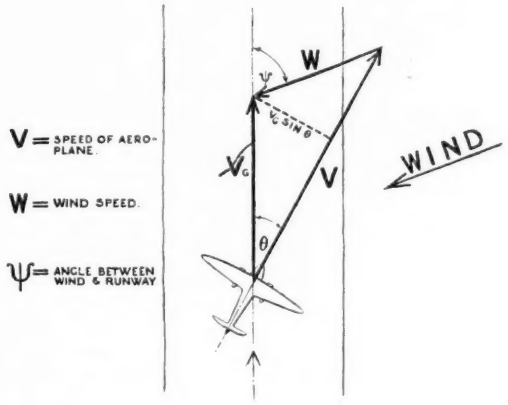


FIG 6

the new proposal to mount the wheels on aircraft, both large and small, well aft of the centre of gravity, and to place the auxiliary steering wheel at the nose instead of at the tail has the effect that in a landing of this nature the instantaneous tendency is for the mass of the aircraft to pull into alignment with the direction of motion, whereas the conventional arrangement has the opposite effect until a large proportion of the weight has been thrown upon the leeward wheel.

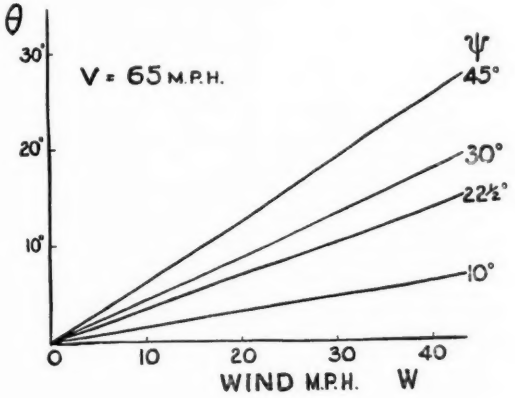


FIG 7

The amount of force exerted upon the aircraft at any moment by the reaction in question depends upon the many factors already mentioned, but the amount of work done is that involved in realigning the aircraft by rotating it about the point of mean reaction of the wheels. Since the tyres are capable of considerable distortion which probably helps them to run on an oblique course, and since adhesion is not perfect, this work may be spread over a period of several seconds,

so that the forces imposed upon the machine are likely to be well below the theoretical maximum.

In Fig. 7 are shown values of θ for winds of from 0 to 40 m.p.h. for an aircraft with landing speed 65 m.p.h. Curves are drawn for values of ψ of 10°, regarded as normal maximum due to error on an all-way field, and for $22\frac{1}{2}$°, 30° and 45° corresponding to the worst condition on a four-runway, three-runway and two-runway aerodrome.

In Fig. 8 values of $V_g \sin \theta$ the apparent drift in m.p.h. are given for similar conditions. It is to be noted that there is very little increase in $V_g \sin \theta$ for winds above 25 m.p.h. While the value increases considerably for values of ψ from 10° to $22\frac{1}{2}$° the increase is much less from $22\frac{1}{2}$° to 30°. We know that $22\frac{1}{2}$°, the four-runway plan, gives satisfactory conditions in practice. The 30° case is very little worse. This seems to constitute a strong argument in favour of the three-runway plan, which may show a saving of from 25 to 30 per cent. in runway cost.

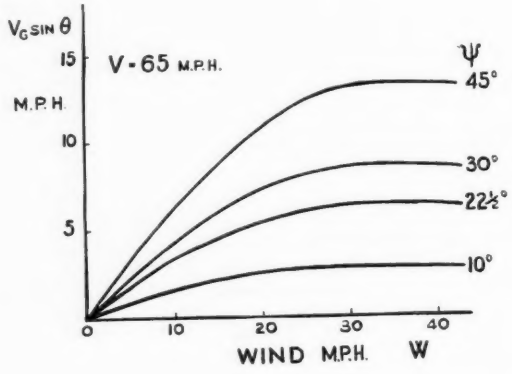


FIG 8

Dimensions of Runways.

The question of length of runway has already been mentioned. Width is likely to be controlled by somewhat different factors. In take-off the track of the aircraft and the degree of accuracy of approach in cross winds and control immediately after touching are additional factors, and the problem of approach and landing during fog introduces further quite different considerations. It appears that contemporary aircraft can be handled with ease upon comparatively narrow runways. In America, 100-foot runways are used successfully on a number of runway fields. In Africa I examined a two-runway field on the Imperial route to the Cape, where one runway was 165 feet wide and the other 195 feet wide, which was regularly used by the largest aircraft. In America, in the winter, I believe that snow is often cleared for a width of no more than 50 or 60 feet, and little difficulty is experienced. The experience of Airwork, Limited, in Iran has also shown that if necessary very narrow strips can be used with safety by medium-sized aircraft. Moreover, the important fact remains that it is always possible to add to the width of a prepared runway.

In planning, however, the line of approach between buildings or obstructions must be considerably wider than any area to be surfaced. For fog landing the Air Ministry specify not less than 400 yards width, and this is certainly not too much with present systems of guidance. Improvement in the visual aids to blind approach landing as well as improved radio guidance and control may in the future

increase accuracy and consequently reduce the width of runway required. None the less, it would seem desirable to preserve approach lanes or flightways of at least 400 yards width in the main directions of landing on major airports, and at least 300 yards width on normal airports in directions other than that used for blind approaches.

LANDING SURFACE.

Consideration of the landing surface must include load bearing capacity, smoothness and wearing capacity. The loads imposed upon the landing surface by large aircraft are already considerable, and there is every indication that they will greatly increase. It is, I think, true that aircraft will be far the heaviest vehicles using pneumatic tyres. At present the maximum wheel load in the country is 7.1 tons in the case of the Scylla, but this will no doubt soon be exceeded. I am informed that the heaviest existing wheel loading in America (the Boeing Bomber) gives 7.15 tons, but that the D.C.4 will give over 11 tons. If a limit per wheel is imposed, it is probable that this will be more on account of the difficulty of stowing a very large wheel retracted than of difficulty in designing wheel and tyre. Tyre pressures in this country run about 3.1 tons per square foot, but there are indications that this pressure may be increased. In America pressures of 3.85 tons per square foot are being talked of. While such pressures will be supported by hard turf, they are approaching the limit for soil in wet conditions. Undercarriages on civil aircraft are normally designed with a safety factor of about 4 which suggests that impacts may impose much greater loads. Until the tyre is flattened down to the rim, however, the pressure per square foot remains more or less constant, owing to the increase in area. Moreover, the impact is a glancing one imposed at a speed of from 30 to 70 m.p.h. in a direction inclined at an acute angle to the aerodrome surface. For these reasons it is usual to regard impact loads as no more serious than static loads. In this country where excellent turf can be grown and kept drained, a grass surface may be expected to support the loads referred to at any points where the amount of traffic does not impose them frequently upon the same point. In all but the driest weather, however, some depression will occur and the resulting resistance to rolling will inevitably affect the take-off.

It is usual to consider this type of resistance together with that due to local undulations, roughness and vegetation, and the friction in the wheel bearings, lumped together as a single coefficient of friction μ.

Diehl in N.A.C.A. Technical Report No. 450 gives values for μ for varying surfaces as follows:—

0.02 smooth deck or hard surface.
0.04 good field, hard turf.
0.05 average field, short grass.
0.10 average field, long grass.
0.10 to 0.30 soft ground, gravel or sand.

He gives a means of calculation of the effect on take-off which is extended by Hartman in N.A.C.A. Technical Note 557. This system has been used by British designers, working with a coefficient of 0.07 and has been found to correspond closely to the results of actual tests. This value of μ may therefore be regarded as the average for good aerodromes in this country. It is necessary in order to apply it to have particulars of the aircraft in question, and I am therefore greatly indebted to members of the design staffs of several well-known firms of aircraft manufacturers for calculations and characteristics from which the figures which follow were derived. The effect of μ upon the take-off run and so upon the pay load or range of aircraft seems of exceptional importance, since this effect can be obtained without increase in the size of aerodrome. An attempt has been made therefore to analyse this effect and to evaluate it in certain cases. I must point out, however, that apart from observed effects for a standard value

of μ of 0.07 the results obtained are theoretical and should be accepted with reserve until they have been confirmed by further tests made upon prepared surfaces.

The characteristics of an aircraft affecting its efficiency for air transport (and incidentally bombing) purpose are cleanness, power loading and wing loading, the latter two being related more particularly to performance and economy of operation respectively.

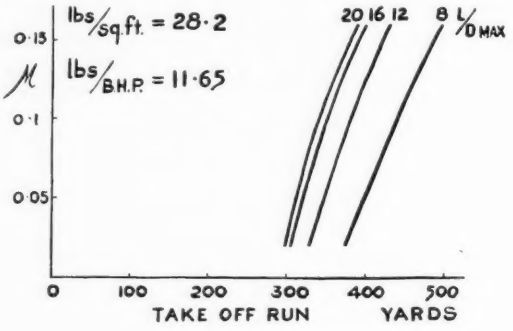


FIG 9

The effects of varying μ with varying lift/drag ratio are shown in Fig. 9, assuming constant wing-and-power-loading. It will be seen that this effect increases in importance with greater cleanness.

In Fig. 10, the effect is indicated in relation to power loading, assuming constant lift/drag and wing loading. Again the effect increases with the decrease in power and so with the economy of the type.

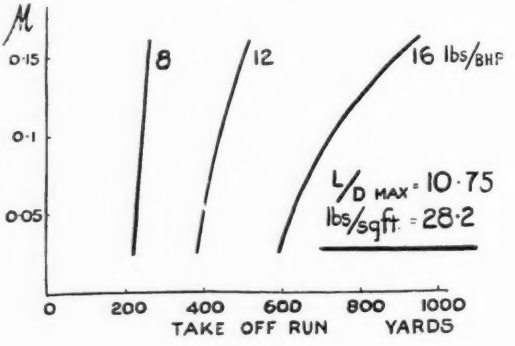


FIG 10

Fig. 11 shows the effect plotted against wing loading, the other factors being constant, and the same tendency is observed. From the above set of curves it would appear that the more efficient and economical aircraft become, the greater will be the importance of μ, and the stronger the case, therefore, in favour of runways of concrete or other smooth hard material.

An attempt to evaluate this effect for two types of civil aircraft has been made. In Fig. 12, case (1) is an existing type of small commercial aircraft upon which tests confirming the accuracy of the formula have been carried out. The all-up

weight is 6,5000lbs. and the power loading 15.85 lbs./h.p. and the wing loading 21.7 lbs./sq. ft.

Case (2) is a hypothetical one based upon the design of a high performance, long-range transport machine at present under construction. Power loading is approximately 14.3 lbs./h.p., wing loading 29.7 lbs./sq. ft. The take-off characteristics of this machine would not obtain a normal category, but the I.C.A.N. screen would be crossed at 850 yards. It is seen that by substituting a hard

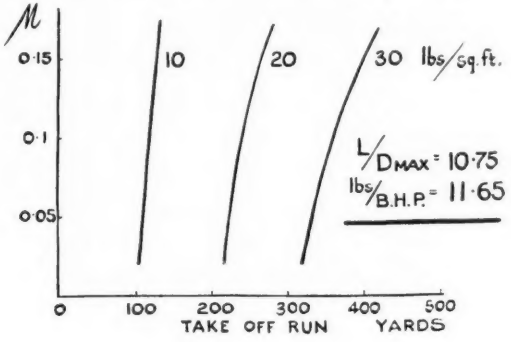


FIG 11

prepared surface such as concrete or asphalt for normal good turf a reduction of take-off run by approximately 20 per cent. is obtained. Even more striking, however, is the effect upon take-off run of bad aerodrome conditions when it is remembered that long grass, soggy ground, soft sand or stony conditions, may increase the value of μ to over 0.10. The effect is, of course, greatest in the case of the long-range transport aircraft. It is clear that airport surface conditions may be closely related to the economics of air transport operation. To give some idea of the effect upon pay load of variations of μ a theoretical calculation

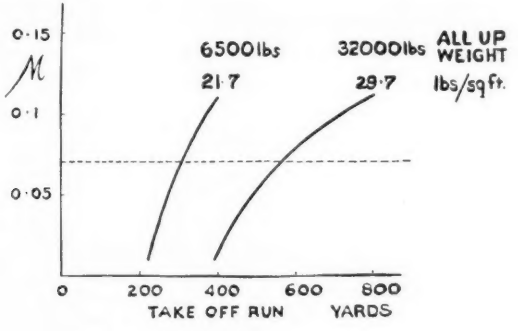


FIG 12

has been made for the same aircraft, and is illustrated in Fig. 13. In both cases the gross weight to give performance equivalent to that on a normal grass aerodrome ($\mu = 0.07$) is calculated for various values of μ between 0.02 and 0.10.

In case (1) it is seen that the variation between a normal aerodrome and smooth hard runway is nearly 5 per cent., equivalent in this case to 22 per cent. of pay load. The variation between a bad grass aerodrome and the runway is about twice this amount.

In case (2) the effect is more striking, being about double that in case (1). The calculated increase of gross weight, which is practically that of pay load, is $1\frac{1}{8}$ tons, representing an addition of 70 per cent. These figures would appear of great significance to airline operators.

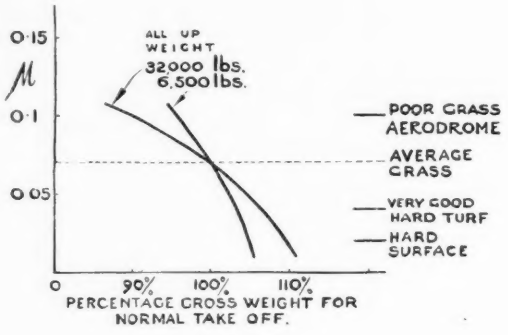


FIG 13

ZONING.

The last question for consideration is the protection of the landing area, whatever its dimensions, against the erection of high obstacles in its vicinity which would render any part of it ineffective. The Air Ministry, for licensing purposes, has defined as an obstruction any object subtending an angle greater than 1 : 15 from the end of the runway area, this angle having been decreased from 1 : 10 for permanent aerodromes during the present year. The British Standard

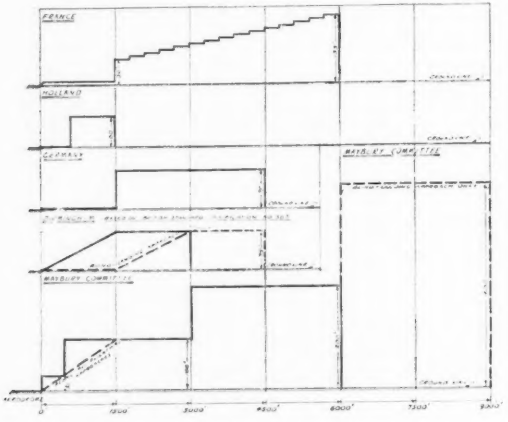


FIG. 14.

Specification for land aerodromes and airway lighting adopts a definition agreed internationally for obstructions in the vicinity of airports upon which obstruction lights must be placed. This definition includes all objects within 500 yards of the boundary subtending an angle greater than 1 : 20 above the horizontal from the nearest point of the boundary, and all objects between 500 and 1,000 yards from the boundary having a height of 75ft. above the boundary at the nearest

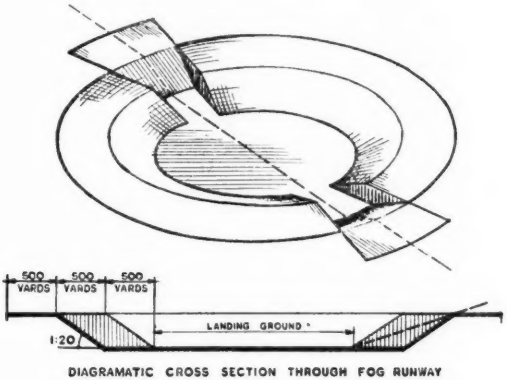
point. Thus it is clear that obstacles exceeding the limits of the British Standard Specification are permissible, but should normally be provided with obstruction lights.

The Air Navigation Act of 1936 gives the Air Minister power to erect lights or warning signals on obstructions in the vicinity of airports likely to prove dangerous to flying, but such obstructions are not defined under the Act. Moreover, the Act does not give power either to remove or control the erection of obstructions except by the process of purchase by the airport authority of the land upon which they are situated and resale with restrictions.

It may be desirable in the case of publicly owned airports to control the erection of obstructions by restrictions under town planning in a way similar to the control of building under the Ribbon Development Act. Alternatively, in special cases when considerable development is in progress in the airport area, powers may be taken by a private Bill in Parliament.

The question arises as to what standard should be adopted for such restrictions.

In this connection it may be of interest, in view of the international character of aviation, to examine the restrictions at present imposed by Governments in countries abroad. These are generally indicated in Fig. 14, in which the definition given in the B.S.S. is also shown. In view of the international character



DIAGRAMATIC CROSS SECTION THROUGH FOG RUNWAY

FIG. 15

of this definition and of the fact that where it can be imposed airport authorities may be relieved of the responsibility of erecting obstruction lights this standard has been adopted at several major airports in this country, notably in the case of Birmingham, where it formed the basis of a private Bill recently passed.

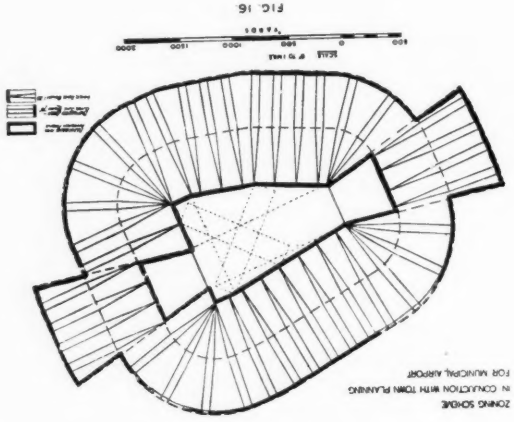
At a major airport where a fog-landing runway for use by heavy commercial aircraft forms part of the airport plan, modification of the zoning to allow a larger margin for error along the line of blind approach and take-off is obviously desirable. At Birmingham this has been achieved by the inclusion of fan-shaped approach areas 500 yards long at the ends of the fog-landing runway.

The effect of these areas is to push the zoning outwards 500 yards at these points, the lateral extent of the fan shape being determined by the extension of diagonal lines drawn across the fog-landing runway. These areas, which would be used for agricultural purposes or as open spaces, would provide sites for marker beacons, and for threshold lighting and other signal apparatus required to assist the pilot. Experience has shown that a pilot approaching in poor visibility by radio guidance must maintain his aircraft in an attitude in which response to the controls is immediate should an emergency arise. There is thus a tendency to come in at a higher speed than in normal visibility. This consti-

tutes a logical argument for providing, at least in one direction, clear approach zones as well as a larger runway on the aerodrome itself.

The effect of this zoning is shown diagrammatically by Fig. 15 and in plan by Fig. 16.

While this zoning has as yet only been adopted in a small number of cases the Air Ministry has stated that it provides a reasonable measure of protection, and it has the further interest of being the only complete system so far established by law.



Since this paper was read a recommendation for " standard zoning " round an airport has been published with the report of the Maybury Committee and is likely to be adopted for town planning purposes. This zoning restricts all obstructions within a circle of 1,350 yards diameter to a height of 35 feet above the mean level of the aerodrome and further imposes a limiting angle of 1 : 15

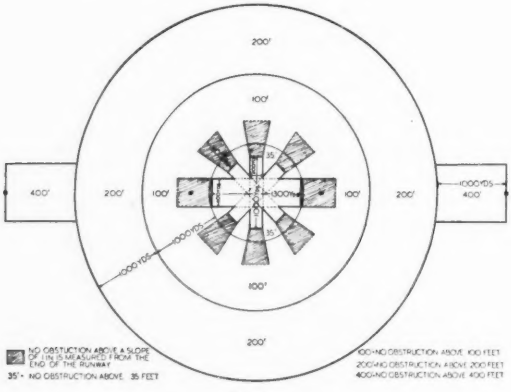


FIG. 17.

from the aerodrome boundary over fan-shaped approach zones extending 500 yards from the ends of each runway. Restrictions to 100 feet and 200 feet are imposed over circular zones 1,000 yards and 2,000 yards respectively from the 35-foot zone; 400-foot zones, 800 yards wide, are extended a further 1,000 yards along the axis of the fog run to include the outer marker beacons. For com-

parative purposes this scheme has been added to Fig. 16 and is shown in plan in Fig. 17.

Conclusion.

From the foregoing brief study of landing requirements it appears that a substantial increase in pay load can be obtained by the aircraft operator if long level runs on a surface having a low coefficient of friction (μ) can be made available.

A concrete or macadam surface offers the advantage of constant resistance in all weathers.

This condition can be most economically achieved by the use of runways. An arrangement of three runways mutually inclined at 60° may be considered a possible alternative to the more normal layout of four runways.

The present technique of landing by radio guidance cannot be reconciled with the use of the comparatively narrow runways that are satisfactory in reasonable visibility. Improvement of this technique will have a vital bearing upon the cost of airports.

The complete availability of the surface for landing can only be obtained by strict control of surrounding obstructions. An area of land not surfaced for landing, but in agricultural use, may be a valuable addition to the landing area.

Finally, since the basic problem is to carry the largest load with the greatest regularity in the most economical manner, close co-operation between aircraft and airport designers is essential. The evidence in the paper suggests that such co-operation could to-day effect an important reduction in ton-mile costs of air transport.

Discussion.

The Chairman: He hoped the three classes of individuals mentioned by the author were represented at the meeting and would have their say in the ensuing discussion. There had not been an opportunity for members to read the lecture in advance; that, unfortunately, was not possible owing to the illness of the author at the time when the lecture would normally have been prepared for advance circulation.

There were two questions he wished to ask. The author had seemed to speak of taking-off at 3,000ft. when the air temperature was 150 deg. at that height. He might have said 115 deg., but if he said 150 deg., then it seemed to him rather hot.

His other question was rather more important. The author did not mention whether anything was being done in the United States on the possible use of screens on aerodromes.

Major R. H. Mealing (*Associate*) (Directorate of Civil Aviation): They would all like to say "Thank you very much indeed" to the author for an extraordinarily interesting lecture. He himself happened to be in the position, probably, of being able to appreciate the contribution which the author had made to the design of aerodromes in this country, almost more than anybody else. Whether the author liked it or not, all his designs had to come to him at some time and he could say that the standard which the author had set in design and the method in which he compiled his reports was a remarkable one, for not only did they include technical data for the benefit of the engineer, but also lucid explanations for the benefit of those not with engineering capacity. It was interesting to see the way in which the author had described how aerodromes were now designed, because if one took one's mind back 20 years or so, there was an extraordinary difference between then and the way aerodromes were considered now. In those early days it was the practice to look for a few flat fields where, by removing the intervening hedges and necessary trees, the resultant would be an aerodrome suitable for use by aircraft of that time. Nowadays one looked in the

correct locality and said to oneself, is it possible to make an aerodrome there complying with all modern requirements. Especially during the past few years had a great deal been learned in this respect. He had been at this work a good many years and was still learning. It was very satisfactory to him that the author had recognised this question of the operators, the aircraft designers and the aerodrome designers getting together because that was extremely necessary. We were continually hearing of the small aerodromes in this country and how aircraft could not operate from them safely under all conditions. On the other hand, the owners of aerodromes said they could not afford these very large aerodromes that were advocated. Both points of view were right in their respective ways and there had to be a compromise which, however, would only be arrived at by everybody getting together. One thing not mentioned by the author—and he was sorry it was not—was the design of aerodrome buildings. It was extremely difficult to get any new designs of aerodrome buildings in these days. An old standard was set up a few years ago and that standard seemed to remain. Passengers came in one way and went out another, and it was the same with freight and an enormous amount of work was entailed. There must be a better design of building possible and he hoped it would be forthcoming before very long.

Sir ALAN COBHAM (*Honorary Fellow*): Major Mealing had expressed most of his views, but he would like to ask one question. A great deal had been heard about the take-off of aircraft and he would like to know exactly what performance that take-off meant, because, with a machine taking-off at a very high speed, the point of unstick and the angle of climb varied considerably, compared with a machine getting off the ground less quickly.

Therefore, he would like to know exactly what the speaker had in mind regarding the relation between the take-off of the aircraft and the rate of climb, because there were differences in the performance of aircraft and a very wide controlled zero line was needed.

Zoning was, of course, a very important point, because it came into the question not only of the landing of aircraft but also of the take-off. If for reasons of bad zoning it was demanded that a machine should have a steep climbing angle, then it was possible to destroy the performance of aircraft. If, as a result of good zoning, a steep climbing angle was not demanded, the machine might have just as good a climb, but such would be far shallower, and the machine could use a greater zone area around the boundaries of the aerodrome. He would be very grateful if the speaker would enlarge on this a little, and say exactly what he had in view.

Like Major Mealing, he would have liked to have heard something about, he would not say the design of buildings, but their layout.

He did not quite agree with Major Mealing that they had the same old design ideas. The opportunity of putting new ideas into practice was the great thing. Many people had ideas on this question of how airports should be laid out as regards the buildings, but these ideas very often startled the people responsible, and that was the trouble.

People liked to be orthodox, and if anybody wanted to branch out into something new, there was the danger of defeating the whole object.

His own view with regard to the design of aerodromes generally was that it was necessary to nurse people, as it were, into it. If one went to a Corporation and said one was going to put up an airport, and if the whole story were told to begin with, and the Corporation were told they were going to have what it was thought they ought to have, the whole thing would be turned down. By the time one had been conferring with the Corporation for three years, however, one would have gently educated them in the matter up to the stage when the Corporation would begin to tell the aerodrome designers themselves all about it! And whereas at first the Corporation had been thinking in terms of an expenditure of £10,000, they would soon be talking of an expenditure of hundreds of

thousands. Nevertheless, this question of the education of those responsible for aerodromes was one of the difficulties which had to be contended with.

Mr. Eric L. Gandar Dower: He suggested that the excellent recommendation of the author that operators, aircraft designers and aerodrome owners should get together might lead to the exploration of aids to efficiency to limit the size of aerodromes.

Something further might be discovered comparable to variable pitch propellers and brake devices. At the same time, he was sure the future would see much larger aerodromes than the lower standards laid down in Air Ministry Pamphlet No. 55 a year or two ago; but it was going to be equally obvious that many towns which had invested heavily in the development of aerodromes were prohibited from extending their aerodromes like a piece of elastic, owing to geographical difficulties and it would be a pity if such towns had to scrap their airports at great loss and build fresh ones.

Therefore, as an aerodrome owner and—as an operator—he felt that possibly too much had been done by the aerodrome owners in the past to encourage inefficient aeroplanes.

If one arrived at a town at high speed and then ran into a wall for lack of efficient brakes, one would not consider the design of motor cars good, and he felt that the design of aircraft might possibly be held back by over-elaboration of airports.

Although it might be somewhat off the point, he might say that he had recently spent five weeks in Norway and had seen what real enthusiasm could do.

In Norway, as was of course well known, the terrain was quite impossible for the construction of inexpensive aerodromes, whereas fjords and waterways were everywhere. For that reason coastal services and private flying had been very largely developed on floats.

At the same time, it was realised that in order to put Norway on the map internationally there must be land aerodromes.

At Oslo sufficient area was being blasted out of the solid rock. Work had been going on for two years and it was expected it would take a further two years to complete.

The aerodrome was being built by the unemployed.

The cost was falling on the taxpayers.

In other towns such as Bergen with a population of only 100,000, an expenditure of £250,000 was being faced cheerfully as the estimated cost of the aerodrome. Therefore, he did not think the municipalities of this rich country with larger town populations should hesitate to develop first class aerodromes.

Mr. C. M. Barter: He suggested the possibility of the classification of aeroplanes into different classes according to the aerodromes they could use and the performance and requirements they had to meet. At the present moment the I.C.A.N. regulations controlled every civil aeroplane and if advantage was taken of concrete runways and zoning, it meant that an aeroplane fitting in with these developments would be quite impossible for operating on anything smaller or on any present-day type of aerodrome. It seemed, therefore, that a special category of aeroplane could justifiably be introduced for long-range types of machine which would be licensed to operate only from certain aerodromes. The only serious problem which then arose was the question of forced landings which presumably would have to be dealt with by some form of jettisoning of the heavy load to get the machine into a small space.

Flight Lieut. R. C. Preston: There was one thing at the back of his mind which he was surprised had not been mentioned. Landing at Croydon to-day was a very different thing from what it would probably be in 20 years' time or less. Supposing that aerodromes of smaller size were built all over the country, as many hoped would be the case, and they were used to the extent it was imagined they would be, how were they going to handle all the traffic by one runway? Would it not be possible to have dual runways to the cardinal points

of the compass so that machines landing would not interfere with those taking-off? That seemed to be one of the great difficulties at big airports at the present time. It was necessary for the pilots to see if there was a board up on the control tower and then perhaps they had to wait for some minutes. It might be possible to mark out an aerodrome experimentally in white stone or with whitewash in that way and educate the pilots in using the runways in a manner which would not cause interference between the ingoing and outgoing traffic, and see what the effect would be on the speeding up of the traffic. Personally, he was very much interested in the Belfast aerodrome, and when he heard from a previous speaker about Norway, it seemed to him there were equal possibilities at Belfast. As the author probably knew, the Belfast aerodrome was to be made on reclaimed land on the edge of the harbour and the idea was a sound one for there was the water adjacent and the city within five minutes. Could the author say what sort of depth the concrete runways had to be made, because if it were possible to make an aerodrome on reclaimed land there was no reason why there should not be a tremendous amount of strength given to it by the use of concrete runways and, after all, Belfast itself was built on reclaimed land? What sort of depth would be required on the sludge of which the site consisted in the first place to get it into use? Further, could the author give an opinion of the impossibility, as he had heard it expressed, of having a site to the north-east of any city where the prevailing wind was supposed to be south-west? It seemed to him that in the near future siting would not matter, because with blind approach becoming possible in emergency, surely it would be possible for it to become a regular feature, if necessary. Finally, there was a great deal of uncertainty at the present moment as to where machines should come in taxying whilst others were going out. It was due to that that Campbell Black lost his life. There was no taxi-ing line and every aerodrome should have this important feature.

Captain L. P. WINTERS: He asked the author if he did not consider that prepared runways of concrete will be necessary on all aerodromes in the future bearing in mind the terrific increase of wheel loading likely. He could visualise aeroplanes being developed which would have a wheel loading that no form of grass land would stand up to no matter how well it was drained or how carefully it was looked after in certain conditions that were encountered in this country in the winter. Therefore he asked if the author did not think that prepared runways would eventually become an essential item for all civil aerodromes dealing with heavy aircraft.

Mr. D. R. PYE (*Fellow*): There was one question which might perhaps be worth asking. Several speakers, including the author, had emphasised the large increase necessary in the size, and also in the number, of aerodromes. It was impossible to make aerodromes on hilly country and the kind of land that was suitable for making aerodromes was precisely that which was suitable for the production of food—nice flat arable land. At the present time this country was dependent for about 20 per cent. of its food requirements upon production within its shores, and he would like to know whether the author had done the necessary arithmetic to estimate at what point these aerodromes of 1,000 acres or more, multiplied by the numbers which he foresaw would have to be scattered over the country in ten years' time, were going to have a serious effect on the potential food productivity of these islands. Perhaps at the moment the question was not of much economic importance, but a little arithmetic would show that if the anticipations with regard to the development of aviation were realised, it might become by no means negligible. The annual products from the best farm land might be worth £20 per acre. At even half this rate, 100 aerodromes of 1,000 acres each meant a dead loss in food production of £1,000,000 per annum.

Mr. ROLF JENSEN: He was disappointed that the author had not mentioned the question of aerodrome buildings, and said that perhaps after all that was wise and the author no doubt appreciated that this was a specialist side of the question and was more a matter of co-operation with another expert than one solely for

an " aerodrome " designer. Nevertheless, it had been interesting to hear such distinguished speakers as the first two mention this same point, because it seemed to indicate a change in the attitude of people concerned with the actual operation side of aviation. He believed he was right in saying that the most important aerodrome in this country was designed without any specialist co-operation and without the services of an architect, and it seemed to him just as foolhardy to plan an aerodrome without the necessary buildings in the first place, and without having expert co-operation in that matter, as it was to try and design an aerodrome without the services of the aeronautical adviser.

Another point which had been raised seemed to him a complete misconception concerning the areas that were available in this country for aerodrome development. The attitude of the last speaker was probably due to living in places such as London in which one saw town all round continually spreading and in the end one was unable to think of, or visualise, any countryside remaining in the whole of these islands. The gentleman who put this question, however, should be reassured about that because anyone who had gone into the question at all knew that the agricultural requirements of this country were not such as to suffer from the lack of land which could be turned over to production. At the present time land was lying fallow and it definitely existed in sufficient quantities to enable them to produce more than twice the quantity of food that was necessary for the whole of the population of the country. Therefore, he did not think that however many aerodromes were projected there would be any danger of what had been suggested coming about.

Finally, Mr. Jensen reiterated that he was pleased to see the new attitude, and with regard to aerodrome buildings especially because without adequate buildings ready to deal with passengers and freight the " aerodrome " would not be required at all and he had no doubt that it was this very fact that had caused the author himself to co-operate with an architect in his schemes.

Mr. R. A. E. Luard: One point which had been stressed during the paper and discussion was the greater pay load secured by increased efficiency in acceleration and take-off, and there was a fair amount of argument as to whether large aircraft should be land machines or machines which took off from and landed on water. The argument in favour of a machine using water was that relatively the sea was interminable and the take-off could therefore be lengthened safely and, of course, there were no permanent obstructions on water so that a machine once it had left the water could carry on at quite a low altitude before gaining height. However, it seemed to him an open question, for with the increased length of runway proposed for the larger aerodromes and the smoothness of the surface, it might well be that the land machine would come back into its own at a later date.

Captain J. Laurence Pritchard (Secretary): He was not sure whether the aerodrome owner and air line operator should operate too closely with the aircraft designer. The position of the aerodrome owner and the transport man was purely that of a buyer. If he bought a motor car he did not co-operate with Lord Nuffield; he just looked around for the car which suited his particular pocket and purposes and if Lord Nuffield could not supply it tried someone else. It was the job of the aerodrome owners and transport people to do exactly the same kind of thing. They must look round and find the best aeroplane for their particular air line. They should have clear ideas of the type of aeroplane they wanted and press the aircraft designer to get as near it as possible. As it was they were rather in a position of accepting the aeroplane as it is and adapting their aerodromes and air line operating to it.

The lecturer had mentioned a weight of about 11 tons per wheel. The speaker believed that a much greater weight would be in existence before very long. With a weight of more than 11 tons per wheel landing at 65 miles an hour, what sort of aerodrome would be wanted for it and what thickness of concrete would

be required to stand up to that increased traffic of this nature which was contemplated in the near future?

Aeroplanes of the future would certainly be in the order of 100 tons weight or more as materials became better and serious problems would arise in landing with these heavy weights at very high speeds. That was one of the reasons he suggested it was necessary to get back to landing at very low speeds.

One speaker had made a very wise remark when he said the design of aircraft was being held back by the aerodromes, and that was exactly what was happening. People were enlarging the aerodromes to suit the aeroplanes, but he urged the operators to stick to their aerodromes and air line organisation. If they did that they would find aeroplanes would get better and better every day.

Mr. M. H. VOLK (*Fellow*): He wished to endorse the Secretary's remarks because he felt it was a great pity the development of aerodromes in this country was being held back to a very large extent by the fact that local physical and/or financial conditions made it almost impossible for a number of municipalities to build aerodromes of the dimensions or with the length of runway now called for, although the towns concerned may be on the route of an important air line. He therefore agreed with the Secretary that they wanted more and more aerodromes in this country, particularly for medium-sized towns, and it was for the aircraft designers to provide the machines suitable for such aerodromes, namely, with a relatively quick take-off and climb, with low landing speeds and at the same time reasonably fast cruising speed.

The CHAIRMAN: The seeming absence of their friends the aircraft constructors might perhaps be an indication that their views on co-operation were exactly the same as those expressed by the Secretary! He then called on the author to reply to the very numerous criticisms and questions which had been put to him.

REPLY TO DISCUSSION.

He would like first to mention the temperature of 150 deg. F. commented upon by the President and said he was not referring to shade temperature. It was possible to get a shade temperature over 110 deg. F., and anyone who had travelled on any of the main air routes would know it was possible to get a sun temperature very much higher than that. He had recently had to investigate what temperatures were being experienced in Persia and found a sun temperature of nearly 190 deg. F., and he did not think that was exceptional. The use of screens, also mentioned by the President, was a subject which was very dear to his heart. He believed it to be an important development in the future. It was a subject to which he would like to devote special study. He believed it was inevitable that as things developed it would be decided to throw a screen round the unloading area for aircraft just as was done for seacraft. A good deal of research was required to ascertain the exact form of screening and that would cost a lot of money. Perhaps the President might be able, in his official position, to influence a certain amount of expenditure in that direction. If that were done he was certain that some most interesting results would be obtained.

After thanking Major Mealing for his very kind remarks, the author said he agreed that the selection of a standard of aircraft requirements must be a matter of compromise. Perhaps the right attitude to take was not to bully the aircraft designer—although it rather seemed that the Secretary would like to bully him—and at the same time not to treat him too gently. Several people had expressed disappointment that no mention had been made of buildings. He would very much like to prepare a special paper on that subject, although it was more a matter for his partner, but he would rather leave it out of the present discussion because he regarded it as a suitable subject for another occasion.

In answer to Sir Alan Cobham, he said the lengths of runways referred to were to the point of unsticking. The question of the rate of climb afterwards would be taken care of by provision of a considerable margin of run beyond this figure.

The Air Ministry requirement for a particular aircraft, for special cases, was twice the run, in which it could unstick, and he believed that was the minimum margin which should be allowed. If a margin of that nature could be provided it should leave room for sufficient acceleration for the aircraft to be climbing at a reasonable rate over the boundary. He sympathised with Sir Alan Cobham in what he said about leading people who were ordering aerodromes gradually to the view of what they ought to have. The question of getting more interesting aerodrome buildings was all a matter of opportunity. It was to be hoped that suitable opportunities would be forthcoming as time went on.

Several speakers had stressed the point that the people to get them out of the present difficulties were the aircraft designers, and some criticism had been offered of them. Although there were none present, he felt he ought to say that the aircraft designer had not done so badly for the industry during the past few years. There were machines which would cruise at 200 miles an hour and the economic range had gone up by leaps and bounds. It was now thousands of miles whereas formerly it had been two or three hundred. Altogether he felt the aircraft designer had done his stuff extremely well. It was perhaps unfortunate from the aerodrome owner's point of view that the aircraft designer had concentrated on the type of machine that had been considered that evening, but possibly at a later date discoveries would lead the aircraft designer in another direction. It was necessary to follow the trend of development in whatever direction it took. In answer to Mr. Dower, he suggested that the first way in which it was possible to aid the owners of small aerodromes had been demonstrated by some of the curves he had exhibited, and that was to reduce μ to the minimum value. That would materially increase the effective capabilities of the aerodrome. What Mr. Dower had said about Norway was extremely interesting and he personally regarded it as evidence of what was bound to happen in the future. At the present time we were only selecting sites where there were a nice few hundred acres of suitable ground, but in time to come it would be necessary to consider landing places in all localities and the problem would become harder and harder.

Another speaker had raised the question of classification of aircraft in relation to the aerodromes from which they would operate. This was already taking place. A recent amendment to the Air Ministry's design leaflets indicated that a special category C. of A. could be issued to long-range aircraft allowing them to be operated off named aerodromes with reduced given take-off. He felt that was an inevitable trend. In the past, and even to-day, the aircraft operator did not know where his machines would be next. It might be on a long route one day and later on it might be operating on another and different route. He looked forward to the time when the machines and the permanent way were ordered together and the maximum efficiency was obtained by a correct combination of the design of both. As far as forced landing was concerned, he hoped the increase in the efficiency of engines and in performance with engines stopped, would more or less eliminate that eventuality. Jettisoning was, of course, an important means of diminishing the resulting bump if a forced landing had to be made, but he was afraid it could not be reduced sufficiently to make very much difference.

A number of questions had been asked by Captain Preston, but as he had indicated in his paper these were questions which he did not feel he should go into detail now. He hesitated to go into the design of runways, which was a problem in itself and one which should be considered in a special paper. Reference had been made to the site at Belfast and he felt that was capable of providing a first class aerodrome. Probably one would be constructed there, although the site presented very difficult problems on the ground. One was the particularly hygroscopic soil there known as sleetch, but again that was a matter which might well provide material for another paper. He agreed with the suggestion that there should be facilities for landing and taking-off simul-

taneously. There were aerodromes in America where duplicated runways existed, one for taking-off and one for landing. Traffic control would be much assisted by a white line down the centre of a runway to keep the two traffics separate, and he believed that that would be done in time at all aerodromes. There should also be a zone restricted to taxying round the aerodrome.

In reply to Captain Winters, the author said that if the principles of his lecture were carried out he was satisfied that an expenditure of some thousands of pounds upon excellent runways would so increase the pay load of aircraft using them that the aerodrome owner could demand an advantage commensurate with the expenditure involved. He hesitated to suggest how the necessary funds might be obtained, but there must be a way of doing it. He, personally, believed that hard surface runways of concrete, macadam or stabilised soil, would eventually be used on all aerodromes that had any great volume of traffic.

The point mentioned by Mr. Pye as to the possibility of land required for food production being taken for aerodrome construction had been partly dealt with by a following speaker. At the same time he did not envisage a great number of very large aerodromes. Indeed, he thought there would only be a few of them and that they would be used for long range services operating between major points of the country, and that much smaller aerodromes would be satisfactory for local services. Perhaps we need not envisage more than half a dozen 1,000-acre aerodromes. In this connection, however, he mentioned that the new principle of drying grass had provided an exceedingly valuable agricultural use for aerodromes in regular use. The grass drying people were happy to cut the grass during the night, to press and dry it and to produce by this means a foodstuff having about three times the nutritive value of the same amount of hay.

The next speaker—Mr. Jensen—he imagined must be an architect, for he had spoken about co-operation between aerodrome consultants and architects, and was pleased to see that the idea of co-operation was developing. The idea of such co-operation, of course, was a fairly old one. It was in 1928 that he first started co-operating with an architect in the building development at Heston aerodrome. It was scarcely fair to point to Croydon even if it was produced without an architect. The buildings were very good in 1928 and they had served their purpose quite well up to now. An example of the attitude of aerodrome designers and architects towards co-operative planning would be seen at the R.I.B.A. exhibition which was to be held at the beginning of next year.

The question of the landplane versus the seaplane had been raised by Mr. Luard. That was an extremely vexed question. His own view was that the landplane had a big future because he did not yet see how the seaplane was going to get rid of its hull, and for really long-range operation at maximum economy it was necessary to envisage machines with no fuselage. Provided aerodromes were available on the scale now envisaged, he believed the big landplane would arrive and would put up a good performance. Indeed, he believed there would be very striking developments in that direction and possibly in time the function of the seaplane and the landplane would become clearly defined. In any case, there must be conditions in which one or the other would inevitably be required. At the present moment the seaplane had just made a jump ahead, but he believed the landplane would catch up.

The Secretary had spoken in the most dispirited manner on the question of co-operation with the aircraft designer. He had said they should not co-operate with him too closely. That, of course, was one way, and perhaps it was a good one! In the earlier stages it was not a bad thing to tell the salesman of a motor car something of the sort of car that was required, even if one did not buy a car, and surely that was a form of co-operation. The Secretary had said he would like to see the aeroplane made to use a small landing ground and to have a low landing speed, but there again he would say that the designer was inevitably following out the trend of evolution, not necessarily his choice, and the airport designer had also to follow that same trend.

He hesitated again to go into the question of the thickness of concrete required for runways as he felt it should come into a paper dealing with the civil engineering aspects of aerodrome construction. All he would say generally was that the design of runways was very similar to the design of roads; the loads imposed were not very different in the one case from the other.

In reply to the important point raised by Mr. Volk, the author said he thought it was time a second category of aerodromes of what he might call the village type was decided upon; in fact, he believed it would be before long. The trouble hitherto had been that the smaller towns had not had the courage to go forward with a small aerodrome and see what use was made of it.

Finally, the author thanked everybody who had taken part in the discussion.

On the motion of the Chairman, a hearty vote of thanks was accorded the author.

NOTES ON THE DESIGN OF AEROPLANES FOR ATTAINING HIGH ALTITUDE.

By Captain F. S. Barnwell, *Fellow.*

(*Lecture read before the Portsmouth Branch of the Society on February 11th, 1937.*)

The design of an aeroplane to achieve the greatest possible altitude is, from one aspect at least, a simple matter, because it is a case free largely from the compromises usually necessitated in the endeavour to meet best the operational requirements of a specification.

The starting off point must be the engine. I do not propose to touch the engine side of the problem, other than to regard the engine as an " embodiment loan " which has been made to the aeroplane designer and for which he has then to design an aeroplane which shall achieve the greatest possible altitude when powered by this engine. Obviously, the main requirement from the engine is that it shall give the greatest possible b.h.p. per pound of its weight at very high altitudes. This means, of course, the highest possible supercharging and rather indicates the air-cooled radial engine because of the inherent low weight per b.h.p. of this type.

To present the case most simply and for sake of brevity, it is assumed that the engine people have done their bit and have produced an engine which can give, say, the following b.h.p.'s at the following altitudes:—345 b.h.p. at 50,000ft., 270 b.h.p. at 55,000ft., 210 b.h.p. at 60,000ft. It is assumed also that the net dry weight of this engine is 1,250lbs.

It is possible to make now an estimate for the " fixed " weights of the aeroplane; the " fixed " weights being such weights as would remain constant for any form or size of aeroplane designed for this particular engine.

" Fixed " Weights.

	lbs.
Engine (net dry)	1,250
Airscrew	180
Exhaust system	20
" Engine cowling " (total)	150
Engine mtg. and " tank bay "	100
Engine controls (all)	20
Fuel and oil systems	20
Total " power plant "	1,740
Fuel (70 gallons)	535
Oil (6 gallons)	60
Fuel tank, with mtgs.	50
Oil tank, with mtgs.	15
Oil coolers, with mtgs.	90
	750

"FIXED" WEIGHTS—*continued.*	lbs.
Flying controls, all	80
Pilot's seat and mtg.	15
Pilot's canopy, with gear	25
All instruments, with mtgs.	100
Oxygen equipment	80
Electrical equipment	80
	380
Pilot with special suit and parachute	230
Total fixed weight at start of flight	3,100

Total weight at "ceiling" taken as 2,620lbs., for it is assumed that 60 galls. of fuel and 3 galls. of oil are consumed.

I think this table of "fixed" weights is largely self-explanatory, but a few words about it are perhaps advisable:—

"Engine cowling" includes the actual ring cowl with its mounting and the sheet metal fairing of the nose of the body around the engine mounting.

"Tank bay" means a bay at the forward end of the body immediately behind the engine mounting, which bay contains the fuel and oil tanks. This bay is assumed of metal construction with sheet metal covering and with a fireproof bulkhead at each of its ends. Fuel and oil tanks being constant, it is assumed that the weight of this part of the body, which contains them, would also be constant.

"Total fuel" is fixed at 70 gallons. This is an original approximation arrived at by assuming that the average b.h.p. during climb is 340 and the average specific fuel consumption about 0.7 pint per b.h.p. per hour, hence that the average fuel consumption is about 30 gallons per hour.

It is practically certain, from all known climb data, that the machine will have reached its ceiling inside two hours. Hence 70 gallons, 60 for climb and 10 for descent and for landing, appears a reasonable trial allowance.

Obviously it is not of primary importance how much fuel is carried at beginning of flight, for it can always be consumed by hanging about near the ceiling; hence it is wise to start off with too much rather than with too little; but fuel weight incurs non-consumable tank weight, so one does not want grossly to over-estimate.

For the case with this specified engine it is assumed then that the total "fixed" weight at beginning of flight is 3,100lbs., and 2,620lbs. at ceiling.

The next question is the type of machine. Which appears better for this particular purpose, biplane or monoplane?

In Fig. 1 are shown suggested layouts for a monoplane and a biplane.

The monoplane proposed is of the "low wing" type with aspect ratio of 7/1.

The "low wing" type is chosen because with this type it is easiest to accommodate the pilot in an enclosed cockpit whilst affording him a reasonable field of vision, and the length of the undercarriage (hence its weight and drag) is a minimum. Probably any small reduction of aerodynamic efficiency for the low wing compared to the mid or high wing types is compensated for by these advantages.

Aspect ratio of 7/1 is chosen as a reasonable compromise.

The induced drag, Di, of the aeroplane may be taken as

$$(2/\pi)\,(W/S)^2\,(1/\rho v^2)$$

where W is the weight, S the equivalent wing span, ρ the air density and v the speed of flight. Hence the induced drag decreases as the wing span increases. The airframe weight, however, will be increased by increase of wing span. It is probable that the chosen aspect ratio of 7/1 at least gives little away.

More research might be done on this matter; this research toward deciding accurately how airframe weight alters with alteration of aspect ratio of the wing surface, with the proviso that the strength and stiffness of the wing surface must remain unaltered and that the stability of the aeroplane must remain unaltered.

Anyhow 7/1 is decided upon for the aspect ratio of the monoplane and from this is obtained that its induced drag

$$Di = 0.091\ (W^2/A\rho v^2) \text{ in lbs.}$$

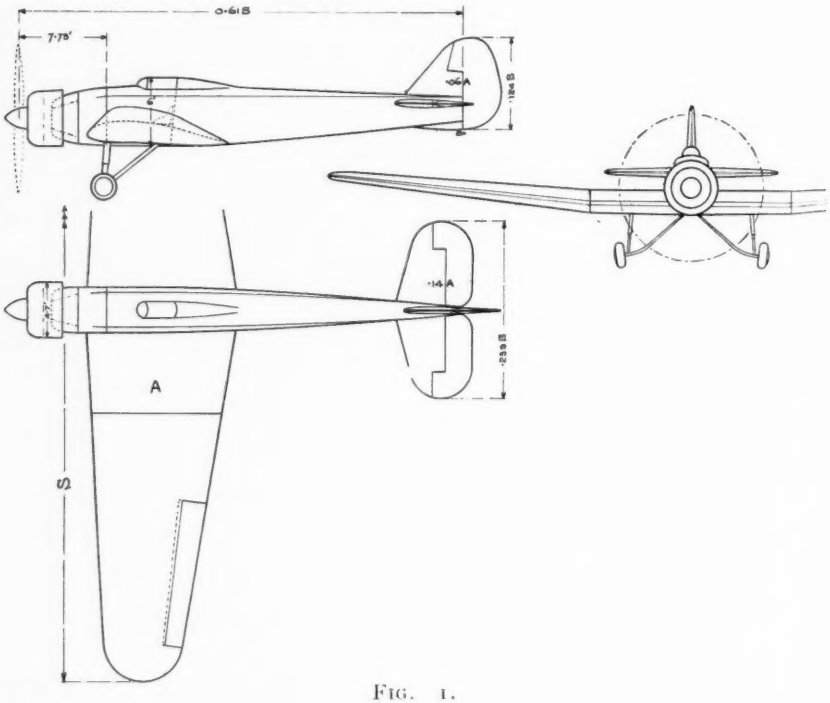


FIG. 1.

where W is total weight of machine in lbs. and A its wing area in square feet.

The biplane proposed is of conventional layout. Equal wings and gap about equal to chord are chosen and an aspect ratio for both top and bottom wing surfaces of 8/1.

This form of biplane has been chosen as giving a reasonable compromise again between aerodynamic efficiency and weight.

As the aspect ratio of each of the two equal-sized superposed wings is 8/1, it follows that $(\text{span})^2 = (8 \times \frac{1}{2} A)$, or $\text{span}^2 = 4A$, where "span" is that of each of the two wings and A is the total area of both wings.

K_B is the "biplane span factor," for this case about 1.12; this value for K_B is quoted from the work of Munk as given in Diehl's "Engineering Aerodynamics."

For this biplane therefore

$$S^2 = (1.12)^2 \times 4\ A = 5.018\ A.$$

Hence is obtained that the induced drag for this biplane.

$$Di = 0.127\ (W^2/A\rho v^2) \text{ in lbs.}$$

where W is total weight of machine in lbs. and A is biplane wing area in square feet.

It should be noted that induced drag is taken here as the wing drag necessary to produce lift of amount equal to the weight of the aeroplane. In other words, it is assumed that the centre of pressure has the same fore and aft location as

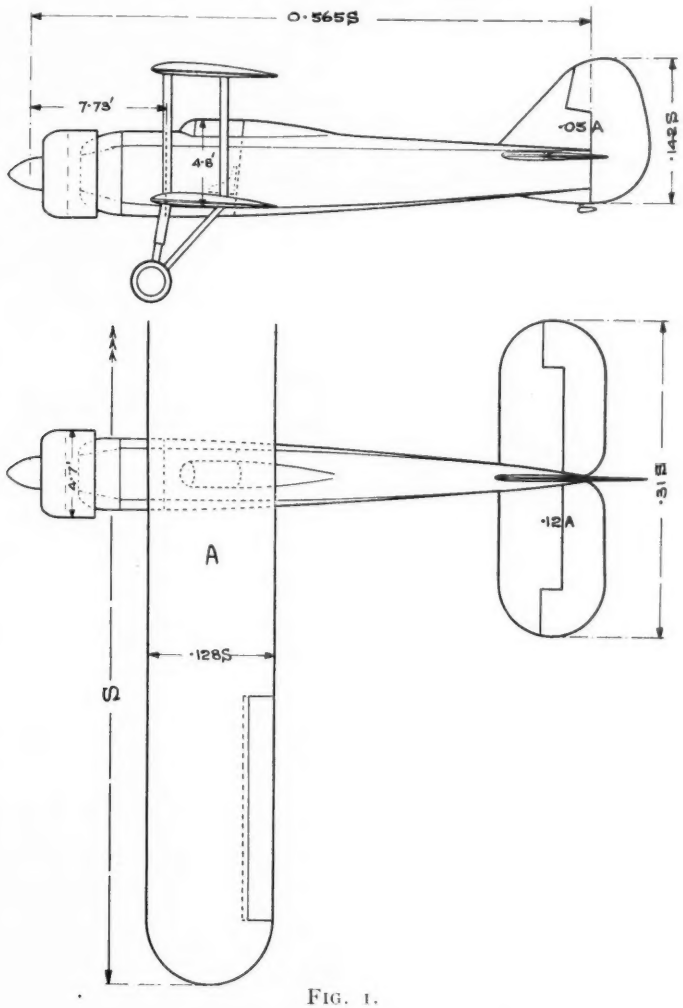


FIG. 1.

the C.G. This is approximately accurate because " climb " conditions are being considered, *i.e.*, high values of K_L.

In " high speed " flight the centre of pressure is almost invariably aft of the C.G., whence a down load is required from the tail to give balance. So in " high speed " flight, the induced drag of the wing is increased because its lift must be greater than the weight, and because there is induced drag on the tail itself, to give the requisite down load. By " tail effect " is meant the increase

of induced drag of the wing plus the induced drag of the tail, occasioned because a down load is required from the tail.

It is assumed that there is no " tail effect " in the case under consideration.

The next requirement is to estimate the " airframe " weights for both monoplane and biplane, for a range of different values for wing area.

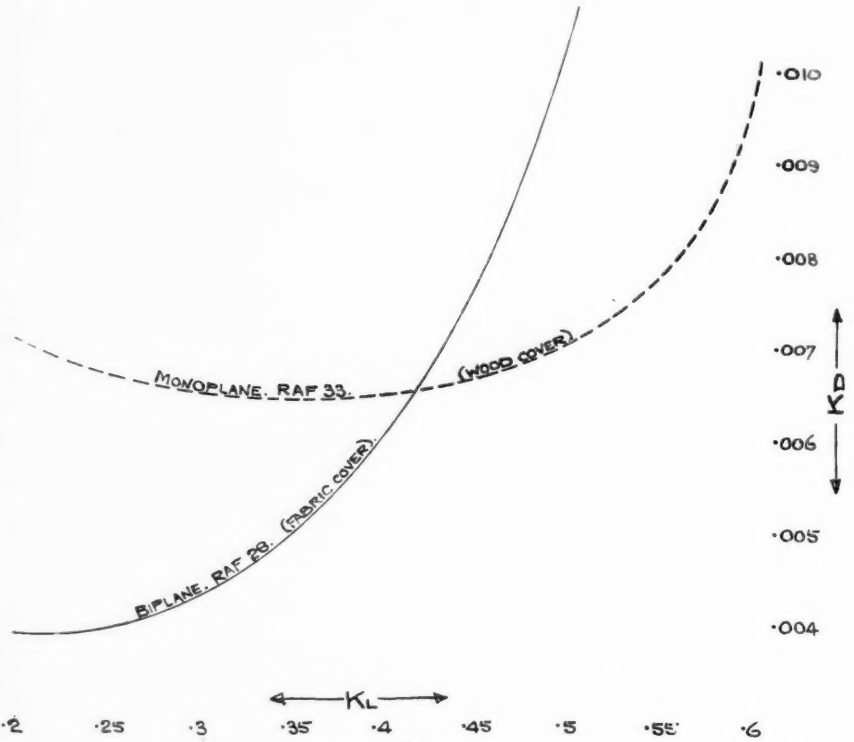


FIG. 2.

For this are used the equations for weight as follows:—

EQUATIONS FOR WEIGHT OF AIRFRAME STRUCTURE.

Wing surface complete, w_W:—

$$w_W = [(A)^{3/2} (F\omega/K_1)(1 - A/K_2)(1 - \{F\omega - 50\}/K_3) + K_4 A] \text{ lbs.}$$

where A = total wing area, sq. ft.

F = load factor, C.P. forward.

ω = unital stressing loading = $(W - w_W)/A$ lbs./sq. ft.

K_1 = 970 for monoplane = 1,080 for biplane.

K_2 = 8,000. K_3 = 1,000.

K_4 = 0.8 for monoplane = 0.50 for biplane.

Body, complete structure and covering, w_B:—

$$w_B = 0.55\ w_W.$$

Tail surfaces (tail plane, elevators, fin, rudder), w_T:—

$$w_T = 0.15\ w_W.$$

Alighting gear (undercarriage and tail skid), w_c:—

$$w_c = 0.047\ W \quad (W = \text{total weight}).$$

Total airframe structure weight, W_s:—

$$W_s = 1.70\ w_w + 0.047\ W.$$

I shall not discuss them here except to state that the basic equation is that which purports to give the weight, w_w, of the complete wing structure. This equation is based on wing area, and on stress loading. It is logically accurate, but the empirical constants may not be correct. They have been obtained from such data as I have been able to analyse.

The calculations for the " airframe structure " weight by the use of these equations is rather laborious, necessitating trial and error methods; but I do not think it could be simplified appreciably whilst retaining logical accuracy.

Below are given the weights of airframe structure for both monoplane and biplane for a series of different wing areas, calculated by use of the equations just given.

ESTIMATED WEIGHTS FOR COMPLETE AIRFRAME STRUCTURE, W_s.

[$F = 7.7$ when $W = 2{,}000$lbs, $= 5.5$ when $W = 10{,}000$lbs.]

$$W_s = 1.70\ w_w + 0.047\ W$$

[w_w = weight of complete wing structure].

Wing Area. A. (sq. ft.)	Complete Airframe Structural Weight (W_s (lbs.). Biplane.	Monoplane.
550	—	2,060
600	—	2,190
650	—	2,310
700	1,900	2,435
750	1,980	2,555
800	2,055	2,675
850	2,135	2,790
900	2,210	2,905
950	2,290	3,020
1,000	2,365	3,130
1,050	2,445	—
1,100	2,520	—

Total weight, W.

$W = (3{,}100 + W_s)$ at take-off.

$W = (2{,}620 + W_s)$ at ceiling.

It may appear rather ludicrous to give figures of weights to fou.-figure definiteness after one has admitted that the constants used in determining such figures may be inaccurate, perhaps by as much as 10 to 20 per cent. But it is justifiable because one is going for comparative figures, and it is probable that from this point of view these weights are accurate to a reasonable degree.

The total weight of the machine, at beginning of flight is the " airframe structure " weight plus the (previously decided) 3,100lbs. of " fixed " weight. This weight is, of course, the one used for stressing, hence in determining the structure weight.

The total weight of the machine at its " ceiling " is the " airframe structure " weight plus 2,620lbs., because 480lbs. of fuel and oil are assumed to have been used up. This weight (at ceiling) is, of course, the weight used to determine the induced drag at " ceiling."

The drag of the wing surface includes " profile " drag as well as induced drag. Induced drag has been dealt with.

The " profile " drag may be considered as the sum of " skin friction " drag and of a certain measure of " form " drag. The " skin friction " drag is, of

course, the product of the skin surface of the wing multiplied by ρv^2 and multiplied by some constant which depends upon the nature of the surface. The "form" drag is really a measure of a certain amount of turbulence, and is dependent upon the shape of the wing and upon the attitude of the wing to its flight path.

In Fig. 2 are given curves for coefficient of "profile" drag, on a base of lift coefficient K_L, for a smooth rigid-skinned monoplane of R.A.F. 33 section and for a fabric-covered biplane of R.A.F. 28 section. These curves have been made up from data compiled by the R.A.E., and are used henceforth.

R.A.F. 28 section has been chosen for the biplane, because this section appears about as good as any other for a biplane.

R.A.F. 33 section has been chosen for the monoplane, because it would seem to give about the lowest "profile" drag at high values of lift coefficient, without excessive shift of centre of pressure. Flight at minimum power involves a high value for lift coefficient, involves in fact a lift coefficient appreciably near to the maximum.

It is as well to note that the wings of the biplane are of constant section throughout their span (except, of course, for the rounded wing tips) and that the quoted structure weights are those for a fabric-covered biplane wing structure, of aspect ratio 8/1. The monoplane wing is tapered both in plan and in thickness/chord ratio, but the section is of R.A.F. 33 type throughout, though increased in thickness/chord ratio (to about 16 per cent.) at the root; the quoted structure weights for the monoplane wing are for the internally-braced type with rigid skin (of sheet metal or of plywood) and of aspect ratio 7/1.

One must estimate now the drag of the remainder of the machine, the "extra-to-wing drag."

Below are given particulars of the methods adopted in calculating this drag.

DRAGS.

Body. Body skin area

Mean girth = 12.2ft. for biplane, = 12.9ft. for monoplane.

Length = $1.13\sqrt{A_w}$ for biplane, = $1.61\sqrt{A_w}$ for monoplane.

$K_D = 0.0021$.

"Skin drag" = $0.0290(\sqrt{A_w})\rho v^2$ lbs. biplane.

= $0.0435(\sqrt{A_w})\rho v^2$ lbs. monoplane.

Constant "form" drag (both)

"Due to engine"	...	...	0.84
"Due to intercooler"	...	...	0.51
"Due to canopy"	...	...	0.15

} = $1.50\ \rho v^2$ lbs.

Tail element (tail plane, elevators, fin, rudder).

$A_T = 0.17\ A_w$ (biplane) = $0.20\ A_w$ (monoplane).

$K_D = 0.0021$ (monoplane). 20 per cent extra for breaks.

$K_D = 0.0025$ (biplane).

Drag = $0.001\ A_w \rho v^2$ lbs. (both).

Undercarriage (including tail skid).

Drag = $(W/4{,}000)\ \rho v^2$ lbs.

[W = full load weight in lbs.]

Body-wing interference drag.

$0.008(\sqrt{A_w})\rho v^2$ lbs. (biplane).

$0.013(\sqrt{A_w})\rho v^2$ lbs. (monoplane)

External struts and wires, biplane.

Drag = $0.0027\ A_w \rho v^2$ lbs.

Miscellaneous $0.17\ \rho v^2$ lbs.

The figures are fairly self-explanatory. It is assumed that the cross-sections of the body are kept constant (because the contents of the body, that is, pilot, controls, tanks, etc., are constant). Hence an alteration of wing area entails an alteration of length only of the body and the body alters in length as does the square root of the wing area.

The mean girth of the body for the biplane is rather less than that for the monoplane. This is necessary because the wing spars of the monoplane are deeper than those of the (bottom) wings of the biplane.

It is assumed that bodies for both machines will be covered by varnished and polished plywood, so a coefficient of " skin friction " drag of 0.0021 is assumed for both.

In addition to the " skin friction " drag of the body, a certain amount of " form " drag must be incurred. It is logical that this added form drag should be taken as the same for both types of machine.

The drag of the tail element needs no comment other than that a drag coefficient of 0.0025 is taken for the tail surface of the biplane, as against 0.0021 for the monoplane, because these surfaces are fabric-covered on the biplane and plywood (or sheet metal) covered on the monoplane.

The drag of the undercarriage is taken as a constant fraction of the total weight W (W being, of course, total weight at beginning of flight). This is logical because airworthiness requirements call for wheel tyres of a projected area (in front elevation) equal to a fixed fraction of the weight.

From all the assumptions made so far, one is in a position to calculate now the total drags for each type of machine for any particular wing area. Total drag, D_T, is the sum of " induced drag," Di, of " parasite drag," Dp, and of increment of drag due to slipstream, δR_1, that is, $D_T = Di + Dp + \delta R_1$.

The induced drag was estimated as

$$0.091\ (W^2/A\rho v^2)\ \text{lbs.}$$

for the monoplane, and as

$$0.127\ (W^2/A\rho v^2)\ \text{lbs.}$$

for the biplane, where W is weight in lbs. of aeroplane at " ceiling " and A is wing area in sq. ft.

The " parasite drag," Dp, consists of the drag of those parts in the slipstream, $K_1\rho v^2$, plus the drag of those parts outside the slipstream, $K_2\rho v^2$. I am sorry to use the term " parasite " drag, but thought it better to call this extra-to-wing drag " parasite " rather than " profile " drag, because I have already called part of the wing drag " profile " drag.

$(K_1\rho v^2 + K_2\rho v^2)$ is multiplied by a factor $[1 + 0.6\ (K_L - 0.15)]$, in other words, the " parasite " drag is assumed to increase as K_L increases. This is reasonable, because the figures for drag of the various elements are drags for these when the aeroplane is in high speed altitude, that is with the body axis approximately parallel to flight path whence a relatively low value for K_L of wings (0.15 or under). If K_L increases, it does so because angle of attack of wing increases and the whole aeroplane is inclined more or less nose-up to its flight path.

The increment of drag due to the slipstream, δR_1, is taken as a linear function of the airscrew thrust T, and as a linear function of the drag coefficient, K_1, of those parts of the aeroplane which lie in the slipstream. The value for here quoted

$$\delta R_1 = (K_1/41)\ T$$

is arrived at by assuming that

$$\delta R_1 = (2\ K_1/S)\ T$$

where S is the mean cross-sectional area of the slipstream.

The figure for this mean cross-sectional area of slipstream is assumed as disc area of airscrew divided by 1.5.

Airscrew diameter is assumed as constant at 12 feet 6 inches, hence its disc area constant at about 123 sq. feet.

From this it follows that

$$\delta R_1 = (K_1/41)\ T.$$

I think it gives a reasonably accurate value.

For level flight, a condition which pertains at the " ceiling," airscrew thrust, T, is equal, of course, to total drag, D_T.

Summing up from all the figures for drag previously given, one arrives at the values for K_1 and for K_2 for both monoplane and biplane as follows :—

Biplane :—

$$K_1 = [0.0017\ A + 0.057\sqrt{A} + W/16{,}000 + 1.5]$$
$$K_2 = [(A - 5\sqrt{A})\ K_D + 3\ W/16{,}000 + 0.002\ A + 0.17]$$

Monoplane :—

$$K_1 = [0.001\ A + 0.0895\sqrt{A} + W/16{,}000 + 1.5]$$
$$K_2 = [(A - 4.73\sqrt{A})\ K_D + 3\ W/16{,}000 + 0.17]$$

Some explanation about these values for K_1 and for K_2 is advisable. The figures for drags of the various elements given previously were the total drags for these elements, whilst here these drags have been divided into those parts in slipstream and those parts outside slipstream before summing up for the totals here given.

This division is made as follows :—

For both monoplane and biplane, all the body, all the tail element, one quarter of the undercarriage and all the body wing interference, are taken as in slipstream.

For the monoplane is taken as in slipstream also, the " profile " drag of the central 12 feet 6 inches of wing span, at a constant " profile " drag coefficient of 0.007.

For the biplane are taken as in the slipstream also, 26 per cent. of the drag of the external struts and wires and the " profile " drag of 20 feet of wing span, at a constant " profile " drag coefficient of 0.004.

The sum of the remainder of the drags gives, of course, that outside slipstream ; " profile " drag of this part of the wings being taken now at the profile drag coefficient, K_D, correct for the value of the lift coefficient, K_L, as already given.

For any chosen value for wing area one is now in a position to obtain the total drag at any chosen value for ρv^2, ρ being, of course, the air density, in slugs per cubic foot, and v the speed of the aeroplane, in feet per second.

One knows the weight and the wing span, hence can obtain the appropriate value for the induced drag. One knows the wing loading, hence the value for lift coefficient, K_L, hence the value for K_D the coefficient of wing profile drag.

One can obtain, therefore, the appropriate values for K_1 and for K_2 ; hence the appropriate values for " parasite " drag and for " slipstream increment."

The thrust horse-power required by the aeroplane for level flight is total drag (in lbs.) multiplied by speed (feet per second) and divided by 550.

This required thrust horse-power will be a minimum for some particular value of ρv^2.

The total drag of the aeroplane will be also a minimum at some value for ρv^2.

But since power required is drag multiplied by speed, it is obvious that speed for minimum required thrust horse-power will be lower than speed for minimum drag.

Actually the speed for minimum required thrust horse-power is pretty near the stalling speed. It is therefore slightly indefinite, because as stalling speed is approached the profile drag of the wing is increasing rapidly and is rather indefinite.

If one assumes that total drag consists of a constant divided by ρv^2 (induced drag) plus a constant multiplied by ρv^2 (parasite drag) ; by differentiating and equating to zero for minimum, one obtains that :—

Minimum drag is attained at that value for ρv^2 at which induced drag is equal to parasite drag, whilst minimum required thrust horse-power is attained at that value for ρv^2 at which induced drag is equal to three times the parasite drag.

This is not strictly accurate because a large part of the " parasite " drag, namely, the " profile " drag of the wing, does not vary as ρv^2, it generally varies less rapidly than does ρv^2, because the coefficient of profile drag generally increases with increase of lift coefficient, as already shown.

On the subject of minimum required thrust horse-power for level flight, the following table is interesting. Here is given for " standard " heights, H, of 50,000, 55,000 and 60,000ft., the air density ρ in slugs per cubic foot.

DENSITIES AND SPEED FACTORS.

H	ρ	$f(\rho)$	$f(v)$
50,000	0.000361	0.1523	2.562
55,000	0.000284	0.1198	2.889
60,000	0.000224	0.0945	3.252

H = " standard " height, feet.
ρ = air density = lbs. per cubic foot/g.
$f(\rho) = (\rho \div 0.00237)$.
$f(v) = 1/\sqrt{f(\rho)}$.

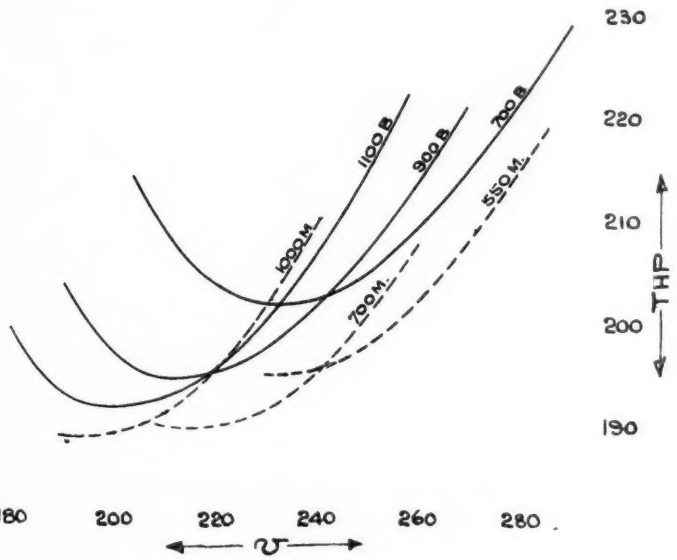


FIG. 3.

The third column, $f(\rho)$, gives the ratio of density, at height H, to " standard ground level " density.

The fourth column $f(v)$ might be called the " speed correction factor."

$$f(v) = 1/\sqrt{f(\rho)}$$

hence $f(v)$ is the factor by which the speed at ground level would have to be multiplied to give the same value of ρv^2. At say, 55,000ft. " standard " height, the speed must be 2.889 times the ground level speed in order to give the same value for ρv^2. It follows then that at 55,000 feet the minimum required thrust horse-power for level flight is 2.889 times what it is at ground level.

The greater the height, the greater is the minimum required thrust horse-power for level flight.

To revert now to the proposed designs for monoplane and for biplane.

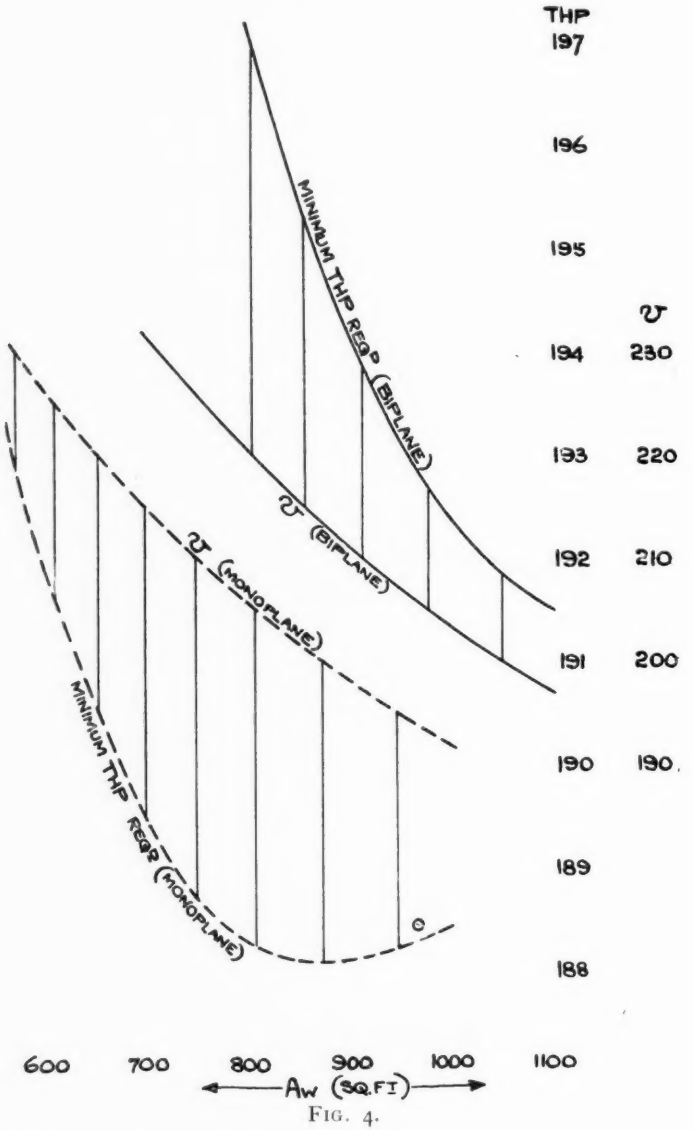


FIG. 4.

For each type, and for each of a series of different wing areas, is calculated the drag at a series of values for ρv^2.

For any particular " standard " height, ρ is fixed, hence v is obtained, hence thrust horse-power required is obtained.

Fig. 3 shows a few sample curves for thrust horse-power required, at 55,000 feet standard height, on a base of speed in feet per second, v.

The numbers attached to the curves give the wing area (in sq. feet); full-line curves (with letter B appended) are for biplane; dotted-line curves (with letter M appended) are for monoplane.

These sample curves indicate that the monoplane is slightly better than the biplane, and that the larger the wing area the lower the minimum thrust horse-power required.

One must emphasise that the validity of these curves depends entirely upon the validity of the assumptions used in arriving at them. I have tried to define clearly these assumptions and to give reasonable and logical arguments for making them. Naturally, however, were any of these assumptions altered, hence weights altered or drags altered, then would these curves be altered.

Working from curves similar to those shown in Fig. 3, one obtains the curves of Fig. 4.

These are curves for minimum thrust horse-power required and for the corresponding speed, at which this minimum thrust horse-power is obtained, on a base of wing area.

It would appear that for the monoplane (dotted line curves), the optimum size for minimum thrust horse-power required is about 870 sq. ft. wing area and that this is attained at a speed of about 200 feet per sec.

The biplane (full line curves) is slightly "off the map;" it would appear that about 1,200 sq. feet and about 192 feet per sec., would be the optimums for it.

These curves are drawn to a very open scale, for illustrative purposes, but it should be noted that there is very little in it. Thrust horse-power required for the 600 sq. ft. monoplane is only about 192 as against the optimum of about 188 thrust horse-power required for the 870 sq. ft. monoplane.

Optimum size of biplane appears to require only about three or four more thrust horse-power than optimum size of monoplane.

This indeterminateness of the optimum occurs more often than not in engineering.

In a way it is annoying, because it makes it difficult for an honest man to declare, with the eloquence of conviction, that any decision is the best.

But in another way it is of comfort, because one may hope that if one's decision is not the best, it is unlikely that it will be appreciably less good than the best.

Taking courage of these findings, therefore, let us decide upon the monoplane and accept these curves (Fig. 4) for minimum thrust horse-power required and for corresponding speed.

So far we have considered only thrust horse-power required, *i.e.*, total drag in lbs. multiplied by speed in feet per second and divided by 550.

But the thrust horse-power given is, of course, the brake horse-power given by the engine multiplied by the efficiency of the airscrew.

Airscrew considerations must be taken into account, therefore, before one can arrive at a final decision on optimum size of aeroplane. Though the minimum thrust horse-power required increases as the size of the aeroplane decreases, yet the speed (at which this minimum is attained) increases also as the size decreases.

Now one may say generally that the efficiency of an airscrew (hence the thrust horse-power given) increases as the speed increases, because its pitch/diameter ratio is increased.

Airscrew considerations are very complicated and laborious, because of the number of variables involved in any general survey.

I attempt here no general survey, but give only the results arrived at by fixing arbitrarily most of the possible variables.

The airscrew has to absorb 270 horse-power at 55,000 feet, and it is assumed that it must do this at 1,320 r.p.m. It is assumed that a four-bladed wooden airscrew is used, four-bladed to keep down tip speed, wooden to keep down

weight. It is assumed that maximum blade breadth is one twelfth of diameter and that pitch is equal to the advance per revolution divided by 0.85.

AIRSCREW (FOUR-BLADED).

To absorb 270 h.p. at 1,320 r.p.m. at 55,000 feet.

v	D	P	E	v_T	δE	E'
190	13.29	10.16	0.739	938	0.056	0.683
200	13.14	10.70	0.755	930	0.053	0.702
210	13.01	11.23	0.769	923.5	0.050	0.719
220	12.89	11.77	0.781	918	0.047	0.734
230	12.78	12.30	0.791	913	0.045	0.746

On these assumptions are obtained the figures given in this table. The first column gives the speed, v, in feet per second. Second column gives diameter of airscrew, D, in feet. Third column gives geometric face pitch, P, in feet. Fourth column gives efficiency, E, assuming there were no loss due to tip speed. Fifth column gives tip speed, v_T, in feet per second, true tip speed $\sqrt{[(\pi nD)^2 + v^2]}$. Sixth column gives decrement of efficiency, δE, due to high tip speed. The last column gives values for $(E - \delta E)$, that is for actual efficiency obtained, E'.

I should state that these airscrew figures were arrived at after a fair amount of consideration of various alternatives. I do not think that appreciably higher efficiencies can be attained with the r.p.m. (of the airscrew) fixed at 1,320.

A metal-bladed airscrew would give definitely lower tip losses at the same tip speeds, but it would have to be of larger diameter to absorb the power, so the tip speeds would be higher. The metal airscrew again would be heavier than the wooden one.

It is probable that it would be of definite advantage to run the airscrew at lower r.p.m. This would mean increase of diameter and of weight, but would mean also increase of pitch diameter ratio (hence increase of E), and decrease of tip speed (hence lower tip losses).

Taking these airscrew findings as they are one can plot now thrust horse-power given against speed. This is done in the chain-dotted curve (labelled THP given) of Fig. 5.

On this same plate is plotted minimum THP required against speed, this by taking values from the curves of Fig. 4, previously shown.

The dotted curve is that of minimum THP required for the monoplane. A similar curve, of minimum THP required for the biplane, is given in a full line, for comparison, although it was decided to abandon the type.

It may be assumed that the point where "THP given" most exceeds "THP required," gives the final optimum when airscrew considerations have been included.

The optimum speed for the monoplane appears to be about 227 feet per second, at which speed there is a surplus of about 8.3 THP.

The optimum speed for the biplane appears to be about 220 feet per second, at which speed there is a surplus of about 1.2 THP.

Turning to Fig. 4 again, one finds that a speed of 227 feet per second calls for a monoplane of 600 sq. feet wing area. Whilst a speed of 220 feet per second calls for a biplane of 800 sq. feet wing area.

It is interesting to note how much smaller is the optimum aeroplane when these particular airscrew considerations are included than when they are not included.

The variable dimensions are given in generalised form in Fig. 1.

Actually, however, the monoplane and the biplane are drawn here to the correct proportions for the monoplane at 600 square feet wing area and for the biplane at 800 square feet wing area. So the two types are shown in correct comparison for the sizes which have been arrived at, by the afore-described methods, as being "optimum."

It would appear then, that for the engine specified, this monoplane design, at about 600 square feet of wing area, should give about the optimum machine for attaining high altitude.

The wing area being 600 sq. feet, the wing span is 64.8 feet, the airframe structure is of 2,190lbs. weight, total weight at start of flight is 5,290lbs., total weight at ceiling is 4,810lbs.

At 55,000 feet standard height, the optimum speed is 227 feet per second (about 155 m.p.h.), hence the value for ρv^2 is 14.63.

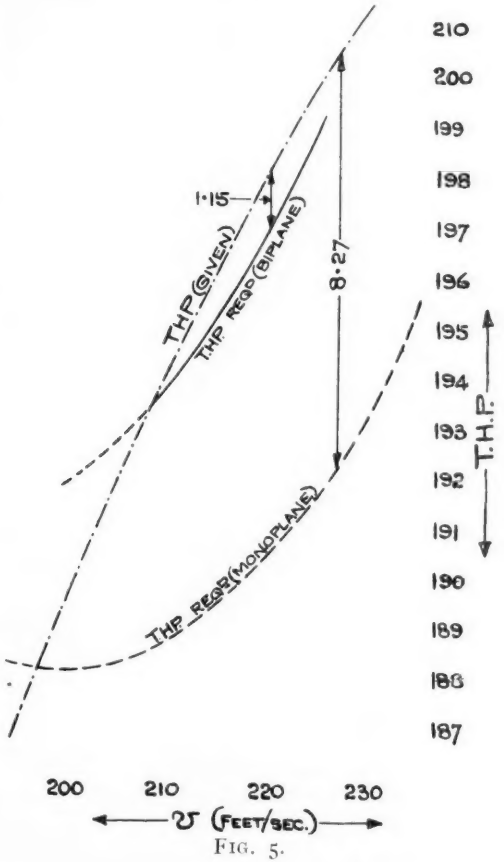


FIG. 5.

The induced drag is therefore 240lbs., the parasite drag is 173lbs., the increment of drag due to slipstream is 53lbs. So the total drag is 466lbs., whence the thrust horse-power required is 192.3.

The airscrew should be of 12.8 feet diameter by 12.2 feet pitch. Its true tip speed, therefore, is 914 feet per second. Hence its efficiency should be about 78.8 per cent. less, about 4.5 per cent. due to tip speed, *i.e.*, about 74.3 per cent.

The thrust horse-power given is therefore 200.6, meaning that there remains a surplus thrust horse-power of 8.3.

The machine should therefore have a rate of climb of about 60 feet per minute at 55,000 feet " standard " height and should achieve an " absolute ceiling " of about 55,600 feet standard height.

That concludes the investigation for the design of a single-engined aeroplane on " conventional " lines. Conventionality does not necessarily mean the best, but it is sound practice, at least in engineering, not to depart from conventionality unless one is certain that there are very good reasons for so doing.

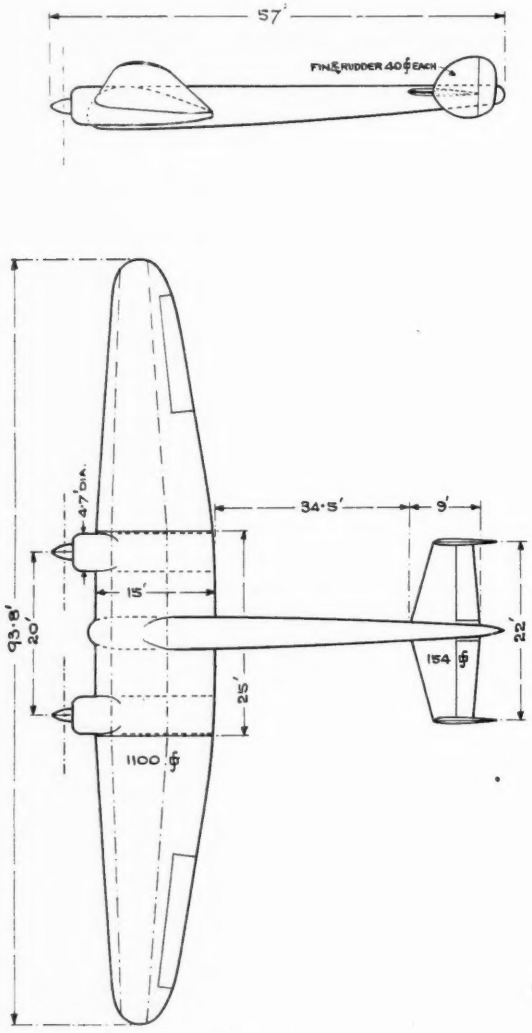


FIG. 6.

Finally, what might one expect to achieve in the near future, assuming the desire to go " all out " for altitude record and assuming that it had been decided that the expenditure of energy and of money was justified.

If the same engine were specified as that for a single-engined machine, I think one should go for a twin-engined monoplane with opposite turning engines and airscrews.

Retractile undercarriages would now pay, as one has the nacelles into which to retract them.

Metal airscrews would probably pay as they could be made reasonably light because they have to absorb very little power for their size, and have to be run " all-out " for limited periods only.

Doubling the horse-power results in a reduction of the weight per b.h.p. of the " fixed " load, because some of this " fixed " load, such as pilot, instruments, etc., is not thereby doubled.

Ducted oil coolers, such as one would use nowadays, would be lighter than the skin surface coolers assumed for the single-engined machine.

The total " fixed " weight for this twin-engined machine should be, therefore, only 5,490lbs. at beginning of flight and 4,530lbs. at ceiling; a saving of 710lbs. less than double the " fixed " weight for the single-engine machine.

As regards airframe structure weight, you will see that an aspect ratio of 8/1 is now proposed, and it is assumed that the relief due to certain weights being distributed now along the wing span should offset the increase of weight due to raising the aspect ratio.

A load factor of 5, C.P. forward, is now proposed; perhaps you noted that the single-engined machine was designed for factors 10 per cent. above civil category. But if a large air liner may have a load factor of five only, surely this special category machine could.

By the same procedure, as outlined before for the single-engined machine, the weights and sizes here proposed have been arrived at.

Wing area, 1,100 square feet.
Wing span, 93.8 feet.
Total weight at start of flight, 9,460lbs.
Total weight at " ceiling," 8,500lbs.
So induced drag, assuming again no " tail effect," is $= 52{,}300/\rho v^2$lbs.

" Parasite " drag is estimated as equal to $8.68\,\rho v^2$. Details are not given, but it might be of interest to note that drag of amount equal to $1.7\,\rho v^2$ is allowed for " cooling drag " plus " form " drag of the two nacelles. Total skin area of body, of tail unit and of nacelles is taken as 1,200 square feet, and for this a skin friction drag coefficient of 0.0021 has been allowed. Coefficient of profile drag of wings has been taken as was shown for the monoplane, in Fig. 2.

K_1, the coefficient for drag of those parts in the slipstream, has been estimated as 3.5. Assuming airscrews of about 14ft. diameter it follows that increment of drag due to slipstream is equal to about 7 per cent. of the thrust.

Examining the case at a standard height of 60,000 feet it would appear that the best speed is about 250 feet per second (170½ m.p.h.) This gives a value for ρv^2 of 14.05 and a value for K_L of 0.55.

To meet best these conditions it would appear that three-bladed airscrews of about 14ft. 6in. diameter by about 13ft. 6in. pitch, running at about 1,240 r.p.m., should be used.

Under these conditions they should absorb each the 210 h.p. given by each engine, and their efficiency (including a tip loss of about 1½ per cent.) should be about 81 per cent.

At 60,000 feet it would appear then that there should be a surplus thrust horse-power of about 33, hence a rate of climb of about 130 feet per minute.

The absolute ceiling should be about 61,400 feet.

THE PART PLAYED BY SKIN FRICTION IN AERONAUTICS.

By F. W. Lanchester, LL.D., F.R.S., Hon. Fellow.

In Part V of my recent paper, when discussing and tabulating the conditions that obtain at low Reynolds numbers (more especially as concerns the dynamics of flight of the model depicted in Fig. 14), the data shown in Table IX and plotted in Fig. 15 need correction. It appears that in the tabulation an incorrect constant was taken. Furthermore, the distinction which exists at low Reynolds numbers between data secured in the wind channel, in which, generally speaking, wind velocity is constant, and the data relating to a glider in free flight in which W is constant, was not sufficiently explained. In this memorandum Tables I and II relate to these contrasted conditions and the derived data given by these tables are plotted in the accompanying figure.

Table I.

V = constant = 10 ft./sec.

$a/2A = 0.038$. $2C_0 = 0.011$.

1	2	3	4	5
K_L	$K_L \times .038$	$+ 2C_0/K_L$	$= K_D/K_L$	K_D
0.6	0.0230	0.00183	0.0413	0.0248
0.5	0.0190	0.0220	0.0410	0.0205
0.4	0.0152	0.0275	0.0427	0.0171
0.35	0.0132	0.0315	0.0447	0.0157
0.3	0.0116	0.0365	0.0481	0.0144
0.25	0.0095	0.0440	0.0535	0.0133
0.2	0.0076	0.0550	0.0626	0.0125
0.15	0.0057	0.0735	0.0792	0.0118
0.1	0.0038	0.1100	0.1138	0.0114

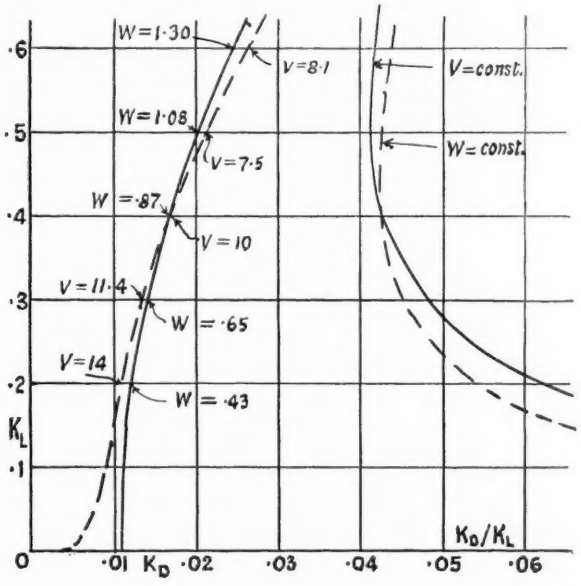
The condition V = const. is that which obtains in the normal course of determinations made in the wind tunnel in which variations in W as consequent on changes of the angle of attack are recorded. In taking the constant value V = 10 ft./sec. it will be seen by reference to Table I that (W = 0.87 poundals) the corresponding K_L value is 0.4, the figures relating to which are underlined in both tables.

Table II.

W = const. = 0.87 poundals.

1	2	3	4	5	6	7	8
K_L	V	N_R	C_0	$K_L \times a/2A$ (.038)	$+ 2C_0/K_L$	$= K_D/K_L$	K_D
0.6	8.1	6.9×10^3	0.0063	0.023	0.021	0.044	0.0264
0.5	8.85	7·5 ,,	0.0059	0.019	0.0286	0.0426	0.0218
0.45	9.3	7·9 ,,	0.0057	0.017	0.0254	0.0424	0.0190
0.4	10.0	8.4 ,,	0.0055	0.0152	0.0275	0.0427	0.0171
0.35	10.6	9.0 ,,	0.0053	0.0132	0.0302	0.0434	0.0152
0.3	11.4	9·3 ,,	0.0051	0.0116	0.0340	0.0456	0.0137
0.25	12.5	10.6 ,,	0.0049	0.0095	0.0392	0.0487	0.0122
0.2	14.0	11.9 ,,	0.0047	0.0076	0.0470	0.0546	0.01092
0.15	16.1	13·5 ,,	0.0045	0.0057	0.0600	0.0657	0.0099
0.1	19.7	16.7 ,,	0.0043	0.0038	0.0860	0.0898	0.0090
0.05	28.0	24.0 ,,	0.0038	0.0019	0.1500	0.1519	0.0073

In Table II, W being constant, the values of V for values of K_L in column 1, are given by the equation, $V = \sqrt{(W/K_L \rho a)}$; from these values N_R are calculated (given in column 3). The appropriate values of C_o are read from the graph in Fig. 2 of the paper, the values of K_D/K_L and of K_D (columns 7 and 8) are calculated as in examples given in Part IV of the paper. These are plotted in the figure. The form of the graph differs from that based on the condition of V = const. This is, and must be always the case, but as the Reynolds number becomes higher the two graphs, shown by the solid and dotted lines, tend to merge, and, as in Part IV, for *high* values of N_R they may be regarded as coincident.



The graphs plotted respectively from Tables I and II relate to the "12.3 gram" gliding model, Fig. 14 in the paper. The graphs are plotted on the basis of theory, and represent theoretical values for K_D/K_L and for K_D as would be determined in the wind channel, V = const. (represented by *solid line*), and for W = const. as relating to a glider in flight (represented by *dotted line*). These are in correspondence when K_L = 0.4 where it will be noted the graphs intersect. When K_L is higher than this value the velocity (W = const.) and consequently the Reynolds number is lower and the performance is worse as shown by the dotted graphs giving higher values of K_D. On the other hand, when the value of K_L is lower, the dotted graph is to the left giving lower values of K_D, indicating better performance. At *high* Reynolds numbers it ceases to be necessary to maintain a distinction between the two conditions, the value of C_o as related to the Reynolds number becomes so nearly constant. As the Reynolds number is increased the two graphs become more and more nearly coincident. The bending of the K_D (dotted) graph towards the origin at the lower end, is due to the fact that as K_L approaches zero, the value of N_R tends towards infinity.

ABSTRACTS AND NOTICES*

FROM THE

SCIENTIFIC AND TECHNICAL PRESS.

Issued by the

Directorates of Scientific Research and Technical Development, Air Ministry.

(Prepared by R.T.P.)

No. 41. MARCH, 1937.

The Forces on a Circular Cylinder Submerged in a Uniform Stream. (T. H. Havelock, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 526-534.) (41/1 3921 Great Britain.)

A solution is given for the two-dimensional wave motion due to a circular cylinder in a uniform stream, taking fully into account the condition at the surface of the cylinder. Expressions for the horizontal and vertical forces on the cylinder are obtained in the form of infinite series of ascending powers of a certain parameter. Numerical calculations are made from these and compared with the known first approximations. The main effect of the additional terms on the wave resistance is to increase the calculated value at low velocities and to decrease it slightly at high velocities.

Correlation Measurements in a Turbulent Flow through a Pipe. (G. I. Taylor, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 537-546.) (41/2 3923 Great Britain.)

A new method for measuring R, the correlation coefficient between two fluctuating currents is described, which has the advantage that small deviations from perfect correlation can be measured accurately. The predictions given by the author in his " Statistical Theory of Turbulence " are verified.

Fluid Friction Between Rotating Cylinders. I—Torque Measurements. (G. I. Taylor, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 546-564.) (41/3 3924 Great Britain.)

The torque between concentric rotating cylinders was measured in two cases, (*a*) inner cylinder rotating, outer cylinder fixed, (*b*) inner cylinder fixed, outer cylinder rotating. It was found, as was to be expected, that the critical speed at which turbulence begins is very much lower in case (*a*) than in case (*b*). The difference between the critical speeds in the two cases becomes rapidly greater as t/R_1 increases, t being the difference between the radii, and R_1 the radius of the outer cylinder. It appears that t/R_1 must be less than 0.001 before the effect of rotation on the critical speed disappears. When the flow is turbulent the effect of rotation on the torque is small in case (*a*) but large in case (*b*).

* In future, by arrangement with the Air Ministry, these abstracts will be published monthly.

Fluid Friction Between Rotating Cylinders. II—Distribution of Velocity Between Concentric Cylinders when the Outer One is Rotating and Inner One is at Rest. (G. I. Taylor, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 567-578.) (41/4 3925 Great Britain.)

Two cases are considered:—(*a*) Inner cylinder rotating, outer fixed; (*b*) inner cylinder fixed, outer rotating. In case (*a*) the distribution of velocity between the cylinders has previously been measured. The far greater technical difficulty of measuring the distribution in case (*b*) has now been overcome by a new design for the inner cylinder. It is found that the stabilising effect of rotation makes it possible for large gradients of velocity to exist throughout the space between the cylinders. The distribution is therefore more like that which occurs in non-turbulent flow than that observed in case (*a*), where nearly the whole velocity changes occur quite close to the wall.

Air Flow in the Boundary Layer near a Plate. (H. L. Dryden, N.A.C.A. Report No. 562, 1936.) (41/5 4169 U.S.A.)

The intensive study of the boundary layer flow near a thin flat plate promises to yield considerable information as to the origin of eddying flow and the effect of turbulence in wind tunnel experiments. The information now available shows that the velocity field varies greatly with the turbulence of the air stream, and with the gradient pressure. The Reynolds number at which transition occurs in a stream without pressure gradient decreases greatly as the turbulence is increased. The presence of fluctuations is not an indication of the presence of eddy shearing stresses. The laminar layer shows speed fluctuations of amplitude considerably greater than that in the free stream. These fluctuations do not produce departures from the theoretical Blasius distribution for laminar flow. They are of lower frequency than the fluctuations in the eddying boundary layer. Transition is a sudden phenomenon, but the point of transition moves back and forth within rather wide limits.

Aerodynamic Characteristics of N.A.C.A. 23,012 and 23,021 Airfoils with 20 per cent. Chord External Airfoil Flaps of N.A.C.A. 23,012 Section. (R. C. Platt and I. H. Abbott, N.A.C.A. Report No. 573, 1936.) (41/6 4450 U.S.A.)

The tests were carried out in the 7 × 10ft. variable density tunnel and covered a range of Reynolds numbers corresponding to the landing condition of a wide range of aeroplanes. From the data obtained, the external airfoil flap in combination with an airfoil appears to be one of the most generally satisfactory high lift devices investigated to date. The combination tested offers a relatively high value of maximum lift coefficient with low profile drag in the high lift range. At low lift coefficients it gives very nearly as low values of profile drag as a good plain airfoil of comparable thickness. Structural and stability problems associated with the large negative pitching moments occurring at high lift coefficients may be slightly greater than in the case of ordinary and split flaps.

On the Air Resistance of Projectiles. (P. S. Epstein, Proceedings Nat. Acad. Science (U.S.A.), Vol. 17, 1931, pp. 532/547.) (41/7 4654 U.S.A.)

Using the equation of Prandtl and Meyer previously developed for supersonic flow "round a corner," the author investigates the flow round a simple polygonal contour. The solution presented only holds provided the velocity exceeds the velocity of sound by a certain amount depending on the angle of the polygon. In this case the change in density in the discontinuity (shock wave) can be found. At speeds below the velocity of sound, no discontinuity is formed, the motion of the gas not differing essentially from that given by potential flow. In the velocity region between that of sound and the minimum discussed above, a dis-

continuity of an unknown type is formed. From these radical changes in type of motion with increase of velocity, the author concludes that the representation of projectile resistance by a single formula (as is often done in practice) must necessarily lead to erroneous conclusions. In the high speed region (*i.e.*, above the minimum velocity) the author's formulæ give resistance coefficients of the same order of magnitude as obtained by experiment on rifle bullets. From this it appears that the heat losses occurring in practice do not affect the resistance appreciably and reasons for this are given by the author.

Air Resistance of Passenger Trains. (Nature, No. 3509, 30/1/37, p. 206.) (41/8 4679 Great Britain.)

The air resistance of a train of conventional British design is equivalent to about 0.0016 V^2 lb. per ton (V = speed in miles/hour). The resistance can be reduced by 20 per cent. with little trouble (engine and first coach) and by 50 per cent. if all smooth coaches are used as well. Theory indicates a possible saving of 75 per cent. Streamlining is more effective in side winds (30° to 60°) than for head-on conditions. A surprisingly large proportion of the air resistance of a coach is contributed by the bogies and undercarriage structure.

Mechanism of the Production of Small Eddies from Large Ones. (G. I. Taylor and A. E. Green, Proc. Roy. Soc., Vol. 158, No. 895, 3/2/37, pp. 499-521.) (41/9 4756 Great Britain.)

The general equations of two-dimensional motion of a viscous incompressible fluid are solved by the method of successive approximation. The original motion is on a definite scale and possesses some of the characteristics of statistically uniform isotropic turbulence. The calculated rate of dissipation is of the same order as that observed in certain tests of grids in wind tunnels.

Wing-Nacelle-Propeller Interference for Wings of Various Spans, Force, and Pressure-Distribution Tests. (R. G. Robinson and W. H. Herrnstein, N.A.C.A. Tech. Report No. 569, 1936.) (41/10 3650 U.S.A.)

An experimental investigation was made in the N.A.C.A. full-scale wind tunnel to determine the effect of wing span on nacelle-propeller characteristics and, reciprocally, the lateral extent of nacelle and propeller influence on a monoplane wing. The results provide a check on the validity of the previous research on nacelles and propellers with 15-foot span wings tested in the 20-foot wind tunnel and reported in Technical Reports 415, 436, 462, 505, 506, and 507. The 4/9 scale propeller and the N.A.C.A. cowling used in the former researches were tested in three typical tractor locations with respect to a thick wing of 5-foot chord and 30-foot span. The span was progressively reduced to 25, 20 and 15 feet and the same characteristics were measured in each case. All important effects of 4/9 scale nacelle-propeller combinations may be measured within practical limits of accuracy by tests of a 15-foot span wing.

The Reduction of Aileron Operating Force by Differential Linkage. (R. T. Jones and A. I. Nerken, N.A.C.A. Tech. Note No. 586, Dec., 1936.) (41/11 4170 U.S.A.)

It is shown that the control force of ordinary ailerons may be reduced to zero over a range of deflections and at a given flight condition by the use of an appropriate differential movement. Approximations to the ideal motion obtainable with a simple linkage are discussed and a chart that enables the selection of an appropriate crank arrangement is presented. Various aspects of the practical application of the system are discussed and it is concluded that a small fixed tab, deflected to trim both ailerons upward, would be advantageous.

The Next Five Years in Aviation. 1.—*Fuels.* 2.—*Diesel Engines.* 3.—*Stability and Control.* 4.—*Size and Performance of Aircraft.* 5.—*Progress in Aeroplane Aerodynamics.* 6.—*Aircraft Structures.* (J. Aer. Sci., Vol. 4, No. 2, Dec., 1936, pp. 74-78.) (41/12 4287 U.S.A.)

Various authors made the following predictions:—(1) *Fuels.* 100 octane fuel will come in general use and higher octane ratings will become available for special purposes. For these high numbers, the rating procedure will have to be perfected. (2) *Diesel Engines.* These will mark time, as carburettor fuel developments appear to offer greater advantages for the spark ignition engine. (3) *Stability and Control.* Large aeroplanes present serious problems which are not overcome by the automatic pilot, but will require special design features. (4) *Size and Performance.* Size will go up to 50 tons gross weight, operational speed 200 m.p.h., operational height 20,000 feet. Arrangement of four engines in a horizontal line will be most common. (5) *Aerodynamics.* Reversible propellers and other methods of speed control will receive attention. Bad weather flying qualities will improve (de-icers, etc.). (6) *Structures.* With increase in size, the percentage of structural weight will decrease from the present 33 to 25 per cent. The stressed skin structure will hold the field as it is definitely superior to alternatives like the geodetic.

Flight Measurements of the Dynamic Longitudinal Stability of Several Airplanes and a Correlation of the Measurements with Pilots' Observations of Handling characteristics. (H. A. Soulé, N.A.C.A. Report No. 578, 1936.) (41/13 4662 U.S.A.)

The dynamic longitudinal stability characteristics of eight aeroplanes, as defined by period and damping of the oscillations, were measured. The observed period increased with the speed of the aircraft from an average of 15 seconds (low speeds) to 45 seconds (high speeds). The damping showed no definite effect of speed. It appears that neither the period nor the damping of the longitudinal oscillations influenced the opinion of the pilots concerning the handling characteristics of the aircraft.

Theoretical Span Loading and Moments of Tapered Wings Produced by Aileron Deflection. (H. A. Pearson, N.A.C.A. Tech. Note No. 589, January, 1937.) (41/14 4788 U.S.A.)

The effect of tapered ailerons on linearly tapered wings is theoretically determined. Four different aileron spans are considered for each of three wing aspect ratios and each of four wing taper ratios. The change in lift on one half of the wing, the rolling moment, the additional induced drag, and the yawing moment, due to aileron deflection, are represented by non-dimensional coefficients. Similar coefficients are given for the damping and yawing moments, the additional drag, and the change in lift due to rolling. It was found possible to effect a fairly close agreement between the theoretical and experimental rolling moments by introducing into the theoretical expression for the rolling moment an effective change in angle of attack obtained from an analysis of flap data. The theoretical curves show that the highly tapered wing with long ailerons has a lower ratio of yawing to rolling moment and a lower additional induced drag than wings with less taper.

Hydrodynamic Tests in the N.A.C.A. Tank of a Model of the Hull of the Short Calcutta Flying Boat. (K. E. Ward, N.A.C.A. Tech. Note No. 590, January, 1937.) (41/15 4798 U.S.A.)

The hydrodynamic characteristics of a model of the hull of the Short Calcutta (N.A.C.A. Model 47) are presented in non-dimensional form. This model represents one of a series of hulls of successful flying boats of various nationalities,

the characteristics of which are being obtained under similar test conditions in the N.A.C.A. tank. The take-off distance and time for a flying boat having the hull of the Calcutta are compared at two values of the gross load with the corresponding distances and times for the same flying boat having hulls of two representative American types, the Sikorsky S-40 and the N.A.C.A. 11-A. This comparison indicates that for hulls of the widely different forms compared, the differences in take-off time and distance are negligible.

Determination of the Characteristics of Tapered Wings. (R. F. Anderson, N.A.C.A. Report No. 572, 1936.) (41/16 4848 U.S.A.)

Tables and charts for use in determining the characteristics of tapered wings are presented. Theoretical factors are given from which the following characteristics of tapered wings may be found:—The span lift distribution, the induced angle of attack distribution, the lift curve slope, the angle of zero lift, the induced drag, the aerodynamic centre position, and the pitching moment about the aerodynamic centre. In addition to the tables and charts, test results are given for nine tapered wings, including wings with sweepback and twist. The test results verify the values computed by the methods presented in the first part of the report. A final section is given outlining a method for estimating the lift coefficient at which tapered wing begins to stall. This method, which should be useful for estimating the maximum lift coefficient of tapered wings, is applied to one of the wings tested.

Propulsion of a Flapping and Oscillating Airfoil. (I. E. Garrick, N.A.C.A. Report No. 567, 1936.) (41/17 4849 U.S.A.)

Formulæ are given for the propelling or drag force experienced in a uniform air stream by an airfoil or an airfoil aileron combination, oscillating in any three degrees of freedom: Vertical flapping, torsional oscillations about a fixed axis parallel to the span, and angular oscillations of the aileron about a hinge.

Full-Scale Span Load Distribution on a Tapered Wing with Split Flaps of Various Spans. (J. F. Parsons and A. Silverstein, N.A.C.A. Tech. Note No. 591, Feb., 1937.) (41/18 4850 U.S.A.)

Pressure distribution tests were conducted in the full-scale wind tunnel on a 2 to 1 tapered U.S.A. 45 airfoil equipped with 20 per cent. chord split trailing edge flaps of various spans. A special installation was employed in the tests utilising a half span airfoil mounted vertically above a reflection plane. The airfoil has a constant chord centre section and rounded tips and is tapered in thickness from 18 per cent. *C* at the root to 9 per cent. *C* at the tip. The aerodynamic characteristics, given by the usual dimensionless coefficients, are presented graphically as functions of flap span and angle of attack as well as by semi-span load diagrams. The results indicate, in general, that only a relatively small increase in the normal force coefficient is to be expected by extending the flap span of an airfoil flap combination, similar to the one tested, beyond 70 per cent. of the wing span.

The Homing Pigeon—What Brings Them Home? (J. F. Vance, Sci. Am., Vol. 156, No. 3, March, 1937, pp. 154-157.) (41/19 4885 U.S.A.)

Although the answer to this question is still to be found, the following facts may ultimately help in obtaining an explanation. (1) The homing pigeon is the only type of bird which possesses the homing ability in any useful degree. (2) Breeding and training can increase the range of flight remarkably. (3) Homing pigeons will fly round storms and fog and generally choose the easiest (not necessarily the most direct route). (4) As a rule, they do not fly at night. (5) They do not require a bird's-eye view of the course. Cases have occurred where the birds, due to wing injury, have walked home. (6) The pigeon's ears

contain a system of semi-circular canals. If ears are stopped or canals injured, the bird appears to lose the homing instinct. (7) The pigeons have remarkable eyesight. (8) Their sense of direction finding is completely upset if released in close proximity to a wireless broadcasting station. On the strength of the above it is suggested that the pigeon in some way reacts to the earth's magnetism and therefore steers a compass course. The world homing record (1931) is 7,200 miles in 24 days (Arras, France, to Saigon, Indo-China). On the above theory, the bird on the outward journey memorised the general magnetic direction. As the bird travelled in a wicker basket in the hold of a ship from Saigon to Marseilles, there was obviously no opportunity for picking up landmarks by eye. Considerable further experiment is, however, required before this theory can be considered as established.

Effect of Several Factors on the Cooling of a Radial Engine in Flight. (O. W. Schey and B. Pinkel, N.A.C.A. Tech. Note No. 584, Nov., 1936.) (41/20 3651 U.S.A.)

Flight tests of a Grumman Scout (XSF-2) airplane fitted with a Pratt and Whitney 1535 supercharged engine were conducted to determine the effect of engine power, mass flow of the cooling air, and atmospheric temperature on cylinder temperature. The tests indicated that the difference in temperature between the cylinder wall and the cooling air varied as the 0.38 power of the brake horse-power for a constant mass flow of cooling air, cooling air temperature, engine speed, and brake fuel consumption. The difference in temperature was also found to vary inversely as the 0.39 power of the mass flow for points on the head and the 0.35 power for points on the barrel, provided that engine power, engine speed, brake fuel consumption, and cooling air temperature were kept constant. The results of the tests of the effect of atmospheric temperature on cylinder temperature were inconclusive owing to unfavourable weather conditions prevailing at the time of the tests. The method used for controlling the test conditions, however, was found to be feasible.

The Quiescent Chamber Type Compression-Ignition Engine. (H. H. Foster, N.A.C.A. Report No. 564, 1936.) (41/21 3964 U.S.A.)

Experiments were carried out on a four-stroke single cylinder engine with a vertical disc-shaped combustion chamber. There is evidence that any air movement that may occur in the chamber has no marked effect on the distribution of the fuel and for this reason the term " quiescent " has been applied. The inferior performance compared with that obtained from the same combustion chamber with forced air flow, despite easy starting, easy scavenging, low mechanical losses and freedom from knock renders this type of combustion chamber unattractive for aircraft engine use.

Heat Loss in High Speed I.C. Engines. (W. T. David, Engineer, Vol. 162, No. 4224, 25/12/36, pp. 675-676.) (41/22 4076 Great Britain.)

Taking recent values for the specific heat and dissociation constants Prof. David has calculated the ideal engine efficiencies obtainable with a number of gaseous fuels. These are compared with indicated efficiency obtained by adding the motoring losses to the b.h.p. In the cases cited, the average difference in efficiency amounts to 2.6 per cent., which, if entirely put down to heat loss, is only half the amount generally accepted. From this the author concludes that the heat loss in practice is really very much less and that the present high speed engines approach much more closely to thermodynamic perfection than is generally supposed.

ABSTRACTOR'S NOTE.—The author's argument rests on the relative accuracy obtainable both for the ideal and indicated efficiencies. If the old heat loss values

are retained, it simply means that the difference between these two efficiencies as calculated by the author is in error by a corresponding amount and it seems that such a possibility cannot be excluded.

The Cracking of Stellited Valve Seats and the Mean Coefficient of Thermal Expansion of Two Stellites. (H. Cornelius and F. Bollenrath, Z.F.M., Vol. 28, No. 12, Dec., 1936, pp. 383-385. Available as Translation No. 414.) (41/23 4348 Germany.)

The mean thermal expansion coefficients of the stellites were obtained between 20°C. and a higher temperature ranging from 100°C. to 850°C. The curves were compared with those obtained for valve steel over the same range. Throughout, the stellite has a smaller coefficient, the mean value being 13.5×10^{-6} and 18×10^{-6} for stellite and steel respectively, over the range 20°-750°C. The cracking of stellited steels is attributed to this difference in expansion and this view is confirmed by micro-photographs of sections.

The Forces and Moments on Airplane Engine Mounts. (P. Donely, N.A.C.A. Tech. Note No. 587, Dec., 1936.) (41/24 4449 U.S.A.)

A résumé of the equations and formulæ for the forces and moments on an aircraft engine mount is presented. In addition, available experimental data have been included to permit the computation of these forces and moments. A simple calculation is made and compared with present design conditions for engine mounts.

Motor Fuel Patent (Addition of Metallic Nitrates). (I. C. Nourse, Chem. Absts., Vol. 30, No. 21, 10/11/36, p. 7823. U.S. Patent No. 2,055,503.) (41/25 3728 U.S.A.)

A small proportion of a nitrate such as that of Cd, U, Al, Fe or K is added and serves to facilitate complete combustion. The nitrate, *e.g.*, Cd $(No_3)_2$, may be preliminarily distilled together with a solvent such as iso-Pr alc. and C_6H_6 and the distillate added to the main body of the motor fuel.

The Kinetics of the Combustion of Methane. (R. G. W. Norrish and S. G. Foord, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 503-525.) (41/26 3920 Great Britain.)

The kinetics of the combustion of methane have been investigated with particular reference to the slow reaction. The velocity of the reaction has been found to be proportional to the square of the concentration of methane and the first power of the concentration of oxygen, and approximately proportional to the total pressure. The effect of surface has been examined and the almost complete inhibition of the reaction in packed vessels confirmed. Ignition has been shown to be a thermal process consequent upon the attainment of a critical reaction velocity. A kinetic mechanism for the combustion of methane has been proposed, based upon the atom chain theory modified to include the phenomenon of degenerate branching.

Relationships Between Physical Properties and Chemical Constitution of Lubricating Oil Fractions. (B. J. Mair and C. B. Willingham, Bur. Stan. J. Res., Vol. 17, No. 6, Dec., 1936, pp. 923-942.) (41/27 4629 U.S.A.)

The following properties were compared: Densities, specific refractions, optical activities, specific dispersions, viscosities, viscosity indices, aniline points, and boiling points. It appears that the least soluble portion of the oil consists substantially of naphthenes (cyclo-paraffins) containing from one to about three rings to the molecule, together with the necessary alkyl radicals. The somewhat more soluble portion consists of naphthenes with more rings, together with some unsaturated hydrocarbons and possibly some aromatic hydrocarbons. Because

of the similar solubility relations, it is possible that in the extraction processes as used at the present time one-ring aromatic hydrocarbons are being discarded to waste along with the undesirable naphthenes containing about six rings to the molecule. This is a point well worth investigating, since these one-ring aromatic hydrocarbons may be a valuable constituent for good lubricating oil.

From the Periodic Table to Production (Discovery of Tetra-Ethyl Lead and Freon Refrigerant). (Chem. and Ind., Vol. 56, No. 6, 6/2/37, pp. 133-136. See also Ind. & Eng. Chem. (Industrial Edn.), Vol. 29, No. 2, Feb., 1937, pp. 241-244.) (41/28 4658 Great Britain.)

On the occasion of his reception of the Perkin Medal, T. Midgley, Jr., gave an interesting account of the discovery of tetra-ethyl lead. Attributing the knocking of paraffin fuel to delayed vaporisation, he attempted to overcome this by dyeing the fuel with some oil soluble dye. A suitable dye not being immediately available, he used iodine and thus discovered its anti-knock effect. As soluble dyes when tried subsequently gave no effect, whilst colourless ethyl iodide worked, the radiant heat explanation had to be dropped in favour of some specific chemical effect. The search was concentrated in that section of the periodic table containing iodine and was soon rewarded by the discovery of the efficiency of diethyl telluride and ultimately by that of tetra-ethyl lead. A similar interesting account of the discovery of the refrigerant Freon (dichloro-monofluoromethane) on the strength of predictions based on the periodic classification is given.

ABSTRACTOR'S NOTE.—The lecturer made no reference to the well known anti-knock effect of iron and nickel carbonyls and it does not appear that their effectiveness could have been predicted from the periodic classification.

Lubricating Bearing Surfaces in Internal-Combustion Engines so as to Prevent Corrosion. (R. C. Moran and others, Chem. Absts., Vol. 31, No. 1, 10/1/37, p. 252, U.S. Patent No. 2,058,342.) (41/29 4795 U.S.A.)

In lubricating bearing surfaces such as those of automobile engines where one of the surfaces is formed chiefly of a Cd or Cu alloy, with a film of lubricating oil which would otherwise tend to develop a corrosive action on the metal, corrosion is prevented by adding to the lubricant a small proportion (suitably about 0.1-1.0 per cent.) of triphenyl phosphite. U.S. patent 2,058,343 relates to the like use of an aryl phosphite such as tri-β-naphthyl phosphite as a corrosion preventive, and U.S. patent 2,058,344 relates to a similar use of tritolyl phosphite.

Electro-Magnetic Control of High Rotational Speed. (T. Davis, Z. Instrum., Vol. 56, No. 11, Nov., 1936, p. 477. Rev. Scient. Instr., Vol. 7, 1936, pp. 96-98.) (41/30 3817 Germany.)

The control applies to air-driven rotors, which are modified so as to act as the rotating magnetic system of a synchronous electric motor, the stationary magnetic field being varied at a definite rate by means of a tuned valve circuit. The modification to the normal phosphor-bronze rotor can be carried out very simply by fitting a short bar magnet immediately above the pivot. The stationary field is wound on a core of silicon steel surrounding the pivot. It is possible to make the drive entirely electric, the air being simply used to float the rotor. Speeds of the order of 1,000-2,000 rev./sec. can be easily synchronised.

Portable Photo-Electric Daylight Factor Meter. (G. P. Barnard, J. Sci. Inst., Vol. 13, No. 12, Dec., 1936, pp. 392-403.) (41/31 3951 Great Britain.)

The practical conditions controlling the accuracy of measurement of daylight factor are considered in the first section of the paper. A simple portable photo-electric daylight factor meter, incorporating two rectifier photo-electric cells, is

described. The direct range of daylight factor measurable by the meter is from 0.03 to 2.5 per cent. The limits of error in the measurement of daylight factor by means of the meter are considered to be about ±10 per cent., so that the accuracy compares favourably with that normally obtainable by visual methods of measurement. No calculation need be involved in practical working, for the daylight factor can be related to the value of a variable balancing resistance included in the meter circuit. Curves relating to daylight factor and resistance are given.

Absolute Viscosity Measurements at the German Reichsanstalt. (S. Erk and A. Schmidt, Z. Instrum., Vol. 57, No. 1, January, 1937, pp. 34-36.) (41/32 4664 Germany.)

Two capillaries of equal diameter, but different length, are placed in series and the relative pressure drop measured, the fluid under investigation being forced through the circuit by means of air pressure and weighed on exit. An accuracy of ±0.2 per cent. is claimed.

The Vaisala Statoscope Applied to Aero-Photographic Survey. (K. Lofström, Z. Instrum., Vol. 57, No. 1, January, 1937, p. 37.) (41/33 4665 Germany.)

The statoscope consists of an enclosed volume of air communicating with a liquid manometer and enables the pilot to maintain constant altitude within ±5 m., the range of the instrument being ±40 m. In case of need for greater accuracy, a photographic recording device can be fitted to the instrument and change of zero during the flight recorded. It is stated that the instrument has given good service in Finland for stereoscopic photographic survey.

New Developments in Photo-Elasticity. (L. Föppl, Z.V.D.I., Vol. 81, No. 6, 6/2/37, pp. 137-141. With bibliography.) (41/34 4729 Germany.)

In photo-elastic investigation of plane stresses, the following fundamental equation is employed

$$\gamma = C\,(\sigma_1 - \sigma_2)\,d$$

where γ = phase difference of two transmitted rays corresponding to a single plane polarised incident ray.

d = thickness of plate.

σ_1 and σ_2 = principal stresses.

C = constant for material of plate.

As long as the stresses are two-dimensional, σ_1 and σ_2 are constant throughout the thickness d. If, however, we consider the three-dimensional case, the phase difference γ of the transmitted rays depends on the variation of σ_1, σ_2 and σ_3 throughout the thickness and its measurement throws no light on the stress distribution. Now experiment has shown that the phase difference γ really depends on the strain or deformation of the material, but as long as the process is elastic the measured γ is proportional to either. If it were possible in a body to remove all stress, but retain the strains, the optical behaviour in polarised light would not be affected. If such a body were then subsequently cut, the various sections, provided they are small enough, could be investigated for their remanent strains by the same methods as already applied to the two-dimensional case. Certain kinds of synthetic resins possess this quality when suitably heat treated and it appears likely that this discovery by Oppel will be of the greatest use in solving three-dimensional problems.

Resistance of Projectile when Passing Through a Rifle Barrel. (Z.V.D.I., Vol. 81, No. 6, 6/2/37, p. 141.) (41/35 4730 Germany.)

The resistance is a combination of friction and work of plastic deformation. The process is too complicated for mathematical analysis and direct experiment

is also very difficult. The procedure has, therefore, been to approximate to practical conditions in the experiment and extrapolate. The following formula is suggested:—

$$R_{max} = C_n (Q - q) \{ a_1/(a_1 + a_2) \} (b_1/b_2)$$

where R_{max} = max. resistance.

Q = max. cross-section of guide ring on projectile.

q = reduced cross-section of ring when passing through rifling.

a_1, a_2 = width of rifling at top and bottom of groove.

b_1, b_2 = width of guide ring under comparison.

C_n = experimental constant.

Causes of the Variation of Sharpness of Vision with Colour of Light. (H. Schober and H. Jung, Z. Instrum., Vol. 56, No. 11, Nov., 1936, pp. 475-476. Zeitschrift f. Techn. Physik, Vol. 17, 1936, pp. 84-93.) (41/36 3816 Germany.)

Chromatic aberration has little influence on sharpness of vision which is mainly a function of wave-length of light and reaches a maximum for wave-length between 5,500 and 5,780 A. The normal mercury vapour lamp radiates in that region and is thus to be preferred to the sodium vapour lamp. The latter radiates principally on longer wave-lengths, as do also high pressure mercury vapour lamps.

The Oscillations of the Atmosphere. (H. Jeffreys and G. I. Taylor, Proc. Roy. Soc., Vol. 157, No. 892, 2/12/36, pp. 535-537.) (41/37 3922 Great Britain.)

Reference is made to a previous paper (Proc. Roy. Soc. (A.), Vol. 156, 1936, pp. 318-326) by H. Jeffreys on the periodic winds associated with a given periodic variation of temperature. The assumption made by Jeffreys is that the temperature at a fixed point in space remains unchanged during an oscillation and this enabled him to derive an expression in the form of an integral through the height of the atmosphere. Prof. Taylor points out that the equivalent height has little connection with the free oscillation of the atmosphere occurring either under isothermal or adiabatic conditions and that the true equivalent height is not expressible as definite integrals through the height of the atmosphere.

Selection of Colours for Signal Lights. (H. J. McNicholas, Bur. Stan. J. Res., Vol. 17, No. 6, Dec., 1936, pp. 955-980.) (41/38 4630 U.S.A.)

Various coloured lights produced by combinations of a tungsten filament lamp and commercially available coloured glass light filters were tested for efficiency and accuracy of identification in each of two six-colour signal systems consisting, respectively, of red, orange-yellow, white, green, blue, and purple lights, and of red, orange, yellow, white, green, and blue lights. The tests were made by 38 normal observers on an outdoor range of 950 feet, for different weather conditions and signal intensities. Comparison between the two systems under prescribed service conditions showed that the use of purple with adequate lamp intensity is preferable to the use of both orange and yellow with red and white. Partial chromaticity tolerances and minimum lamp intensities have been determined for the six-colour system containing purple.

Electrical Stimulation of the Human Cochlea. (Nature, No. 3,509, 30/1/37, p. 192.) (41/39 4677 Great Britain.)

It has previously been shown that stimulation of the human cochlea by audio frequency alternating currents results in a sensation of tone corresponding in pitch to the frequency of the stimulation. There is a possibility that the mechanism of excitation is by direct stimulation of the cochlear nerve fibrils. As an alternative, the authors suggest that the stimulation is indirect, the cochlear

elements which normally are set in motion by physiologically applied sound waves being now stimulated in a manner not yet understood. The arguments are mainly based on the observation of a phase change beat under electrical stimulation. The movement theory of cochlear response is thus confirmed.

First Aid in Case of Burns. (Autom. Tech. Zeit., Vol. 40, No. 1, 10/1/37, p. 24.) (41/40 4694 Germany.)

A burn should never be treated with water. Bathing with oil often leads to complications, since the oil is seldom sterile. As a result of considerable experience, the author recommends treating the wound with absolute alcohol and subsequently with a 5 per cent. tannin solution. It is most important that the treatment should be applied immediately after the accident, as a delay of a few minutes may seriously affect the possible recovery. The tannin treatment has reduced mortality from 30 to 2 per cent. in cases of extensive burns.

Atmospheric Oscillations. (C. L. Pekeris, Proc. Roy. Soc. (Series "A"), Vol. 158, No. 895, 3/2/37, pp. 650-671.) (41/41 4757 Great Britain.)

Assuming the Whipple temperature distribution for the atmosphere between 30 and 60 km., it is possible to find a temperature distribution above 60 km. such that the atmosphere has a free oscillation period very close to 12 solar hours. It is also found that another mode of oscillation of a period of 10½ hours and having no nodal surface exists. Experimental results based on barometric oscillation (12-hour period) due to tidal resonance are thus reconciled with geophysical phenomena (speed of sound wave of Krakatau eruption points to a period of 10½ hours).

Colour Photographs for Aerial Survey. (A. Meilbeck, Z. Instrum., Vol. 57, No. 1, January, 1937, pp. 37-38.) (41/42 4666 Germany.)

The two-lens camera takes simultaneous pictures (9 by 12 cm.) through suitable red and green filters. Subsequent observation is binocular, each plate being suitably illuminated and the two sets of rays being made to overlap. Provision is made at the same time for the uniform projection of a blue light over the whole field of view.

Oscillations in an Electro-Mechanical System. (L. W. Hussey and L. R. Wrathall, Bell Tele. Pubs., B-940, July, 1936.) (41/43 3683 U.S.A.)

Experimental results are given obtained with an oscillating electro-mechanical system in which, under a single frequency impressed electro-motive force, mechanical vibrations are sustained at a frequency near the resonant frequency of the mechanical system and electrical oscillations at the difference between the frequency of the mechanical vibration and that of the impressed force. The system is one studied analytically by R. V. L. Hartley in an accompanying paper. Its performance conforms to the principal operating features predicted in his analysis.

The Present Limitations and Future Possibilities of Voltage Amplification by Their Thermionic Valves. (F. M. Colebrook, J. Sci. Inst., Vol. 13, No. 12, Dec., 1936, pp. 381-385.) (41/44 3950 Great Britain.)

There are at present two principal limitations to the useful voltage amplification obtainable by means of thermionic valves—noise and inability to handle high frequencies. Noise is partly due to thermal agitation and partly electronic. More exact knowledge of the cause (especially at radio frequencies) is required before remedies can be indicated. The inability to handle high frequencies is bound up with the transit time of the electron. In ordinary valve structures, this is of the order of 10^{-9} sec. and thus approximates to 10 per cent. of the period

of a 3 m. wave. This calls either for reduced dimensions of the valve (so-called "acorn" type) or the adoption of a curved path for the electrons (magnetron valve).

Application of Conventional Vacuum Tubes in Unconventional Circuits. (F. H. Shepard, Jr., Proc. Inst. Rad. Eng., Vol. 24, No. 12, Dec., 1936, pp. 1573-1581.) (41/45 4102 U.S.A.)

The following circuits are described:—(1) A two-stage photo amplifier relay circuit operating directly on the alternating current line and using a voltage divider, one resistor and three condensers as circuit parts. (2) A sensitive photo amplifier circuit using a pentode as the load resistor for a photo tube and a standard tube as a reliable and sensitive electro-meter tube feeding a low priced indicating instrument. (3) A modification of (2) to provide variable range, variable sensitivity characteristics. (4) A simple vacuum tube circuit in which standard unselected tubes can be used to multiply currents of the order of 10^{-12} amperes by a definite factor (fixed by the circuit elements and not by the tubes) to such values that they can be easily read on an insensitive milliammeter. (5) A simple capacitance operated relay working on the alternating current line, using metal tubes and only a few inexpensive circuit parts.

Concerning New Methods of Calculating Radiation Resistance, either with or without Ground. (W. W. Hansen and J. G. Beckerley, Proc. Inst. Rad. Eng., Vol. 24, No. 12, Dec., 1936, pp. 1594-1621.) (41/46 4103 U.S.A.)

New general methods of computing radiation resistance, either with or without ground, are described and illustrated by examples. The formulæ are general, exact and practical, and allow the calculations to be made for any form of antenna over a plane earth of arbitrary characteristics. As the mathematical basis of these methods has been explained elsewhere the present paper gives no proofs or derivations of formulæ, but rather illustrates the method of use of the theory by computing radiation resistances for a number of typical antennæ. In connection with these computations various time-saving graphical methods are explained and tables of functions and expansions useful in the calculations are given.

On the Nature of Atmospherics. (E. V. Appleton and F. W. Chapman, Proc. Roy. Soc., Vol. 158, No. 893, 1/1/37, pp. 1-22.) (41/47 4207 Great Britain.)

A series of observations on rapid changes in the earth's electric field associated with lightning flashes has been made, using a Wilson sphere as the exposed conductor and a cathode ray oscillograph with photographic registration. The measurements have included observations both on the time change and the rate of change of the electric field. From observations made at increasing distances from the discharge, the evolution of the atmospheric wave form has been studied. At a distance of about 40-60 km. the radiation field of the atmospheric is approximately equal to the electrostatic field change of the main discharge.

The Effect of a Vertical Dipole Transmitter on a Plane Earth at Distances of the Order of a Wave Length. (K. F. Niessen, Ann. d. Phys., Vol. 28, No. 3, Feb., 1937, pp. 209-224.) (41/48 4663 Germany.)

The author shows how to modify the well known Sommerfeld equations so as to make them applicable at short distances from a dipole. The correction terms are tabulated and depend on whether the electrical or magnetic force component is measured at reception. In a subsequent publication the author intends to deal with distances up to several wave lengths. The results are of importance for determining the strength of a transmitting station from field measurements carried out in the vicinity.

Centimetre Radio Waves. (Nature, No. 3509, 30/1/37, p. 201.) (41/49 4678 Great Britain.)

Details of a split anode magnetron valve are given, the outside diameter of the glass envelope being 0.45 cm. This valve produced waves 0.64 cm. long readily detectable at 15 m. Whilst such substances as black paper, ebonite and wood are transparent to the waves, it appears that their absorption by the water vapour in the atmosphere is such as to render doubtful their application to radio communication.

The Surface Wave in Radio Propagation Over Plane Earth. (C. R. Burrows, Proc. Inst. Rad. Eng., Vol. 25, No. 2, Feb., 1937, pp. 219-229.) (41/50 4893 U.S.A.)

The results of Weyl for radio propagation over plane earth are found to differ from those of Sommerfeld by exactly Sommerfeld's surface wave. Experiments conducted under conditions in which these two theories differ greatly are entirely consistent with Weyl's results and show that Sommerfeld's surface wave is not set up by simple antennas. Accordingly the Sommerfeld-Rolf curves are in error for all conditions for which the dielectric constant cannot be neglected.

Partial Suppression of One Side Band in Television Reception. (W. J. Poch and D. W. Epstein, Proc. Inst. Rad. Eng., Vol. 25, No. 1, Jan., 1937, pp. 15-31.) (41/51 4894 U.S.A.)

An experimental and theoretical study was made for the purpose of determining the advisability of operating a television system with the carrier located near one edge of the over-all selectivity curve. Satisfactory results are obtained when operating a television system with the carrier at one edge of the over-all selectivity characteristic. The fact that fewer stages of amplification are necessary in the intermediate frequency amplifier of the receiver, when the carrier is tuned to one edge of the intermediate frequency selectivity curve, makes it very desirable to adopt this system.

REVIEWS.

AEROPLANE AND ENGINE MAINTENANCE.

By Daniel J. Brimm, Jun., B.A., M.A., and H. Edward Boggess. Published by Sir Isaac Pitman and Sons, Ltd. Price 7/6.

This book is written primarily for the American aeroplane mechanic, and it appears to contain everything which a mechanic is likely to want to know and everything which he is likely to be able to learn from study.

Printed in a type resembling typewriting, it starts by giving notes on the reading of drawings, follows with methods of testing, wood construction, stresses, fabric work, rigging and maintenance, instruments, engines, with notes on accessories, almost every paragraph having an illustration showing exactly what is being discussed.

It not only tells the mechanic how to do the job, but tells him why it should be done in a particular manner, and further, encourages him to understand the machines he is dealing with. There is also a drawing of a section of a typical wing, with its performance curves, and a full explanation.

It is really difficult to see what more can be done for the mechanic than is done here. The only possible criticism from the British point of view is that American standards, examples and practice are always referred to, but that does not prevent it being a book which should be invaluable to every British mechanic. Those of higher rank will learn much from a perusal of this work which can be thoroughly recommended to everyone concerned.

KONSTRUKTIONSELEMENTE FUR DEN FLUGZENGBAU.

By Gerhard Otto. C. J. E. Volckmann Nachf E. Wette, Verlagsbuchhandlung, Berlin, Charlottenburg 2.

Dipl. Ing. Otto is the senior assistant at the Aerodynamics and Flight Technique Dept. at the Hannover Technical High School. In his book, he has set out to provide a systematic outline for the design of an aeroplane, and so well has he done this that the book must be of interest and of great use to all aeroplane designers. To begin with, it is a carefully thought out method, and a great number of tables, graphs, and illustrations make it of use to anyone with a slight knowledge of German.

The question of weight control and estimation, one on which innumerable machines have been spoilt, is given prominence and there are many useful weight estimation curves and tables for modern machines. This is followed by information on the strength of materials and a very useful set of clear drawings showing various structural methods in wood and metal.

There is also a large section devoted to stressing, although this is merely a summary of formulæ with worked examples rather than a theoretical discussion of the mathematical derivation of the methods.

There is really no theory in the book as it is obviously intended to supplement textbooks rather than replace them. In this it is more of the nature of a handbook of limited scope and increased detail.

If there is any outstanding fault it is that the book is not long enough, although the very concise method of presentation of data may perhaps give an unfair impression. However, there are quite a number of problems in aeroplane design which one would like to see dealt with in the manner used by the author of this book.

THE CONSTRUCTION OF WOODEN AIRCRAFT.

By S. F. Wilkinson, A.R.Ae.S.I. Published by Sir Isaac Pitman and Sons, Ltd. Price 10/6.

It is difficult to surmise the reason why this book has been written in this form. It is stated that the intention is to enable practical workers in the aircraft industry to fill up gaps in their knowledge, but it is not easy to see how this can be done by a detailed account of a wooden aeroplane when probably 90 per cent. of aircraft workers are building aeroplanes in metal.

Although much of the construction of the described aeroplane is detailed in drawings, there is no general arrangement, the seating accommodation is not shown anywhere, and the author states that he does not claim that the machine will fly when built, or that it is aerodynamically sound. What, then, is the use of describing it in so much detail?

All the information that it is intended to convey could have been better given by describing typical parts, and this method would have had the important advantage that alternative constructional methods could have been described. As it is, many of the constructional details would be useless for a machine of different type.

Generally, the detailed accounts of manufacturing methods are involved and consequently difficult to follow; while there are a number of points in the construction of the machine which are open to criticism, such as the detailed design of the engine bearers and the absence of torque bracing in the cantilever wing.

The 613th Lecture read before the Royal Aeronautical Society since its foundation on January 12th, 1866.

PROCEEDINGS.

A meeting of the Royal Aeronautical Society was held in the Lecture Theatre of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2, on Thursday, December 17th, 1936, when a paper on "Profile Drag," by Professor B. Melvill Jones, was presented and discussed.

In the chair, Mr. H. E. Wimperis, M.A., C.B.E., F.R.Ae.S. (President of the Society).

The PRESIDENT: Professor Melvill Jones had been Professor of Aeronautical Engineering at Cambridge for 17 years. He had first known Professor Melvill Jones as a gallant pilot and scientific officer at Orfordness during the war; he had formed then and he still carried a vivid memory of his amazing energy and enthusiasm; none of that energy and none of that enthusiasm had shown any lapse with time.

PROFILE DRAG.

By Professor B. MELVILL JONES, A.F.C., M.A., F.R.Ae.S.

Thanks to the pioneer work of Lanchester and Prandtl everyone seriously interested in aeronautics has nowadays sufficiently clear ideas about the power and the associated drag which are essential for the support of an aeroplane in flight. This induced drag, as it is now called, can be calculated with an accuracy which is ample for most practical purposes, and even with the very clean aeroplanes of the present time it contributes, at and above cruising speed, a minor part only to the total drag. We are equally familiar with the idea that the remainder of the drag—the drag involved in getting the aeroplane through the air as opposed to holding it up—can be reduced, by careful design, nearly to the mere skin-friction of the air rubbing over exposed surfaces; the reason being, of course, that the pressures on the surface of a well streamlined aeroplane are so distributed that their horizontal components form an almost completely balanced system.

When I last lectured to this Society on the subject of drag, some seven years ago, the drag of the typical aeroplane was many times greater than skin-friction, and the problem then before us was so to improve external form as to eliminate the large drags arising from imperfect streamlining. It was at that time sufficient to know that skin-friction could be roughly represented by a single coefficient, and the figure which I quoted as a conservative estimate can be represented by the equation $C_f = 0.0040$.* Now, however, so much care is being taken in laying down the lines of new aeroplanes that skin-friction is responsible for the greater part of the whole drag, and it becomes necessary to study in more detail the factors which control its magnitude in various circumstances.

During the past few years the fluid mechanism by which skin-friction is applied to the surface of an aeroplane has been intensively studied in many laboratories throughout the world, with the result that we now know much more about it than we did a few years ago, though not as much as we would like to know and hope to know in a few years time. The object of my lecture to-night is to discuss

* The coefficient was actually quoted in the form K_D = (skin-friction per unit area) / $\rho U^2 = .0020$, where ρ represented density and U velocity. Since that time the conventional coefficient used in this country has been changed to the form C_f = (skin-friction per unit area) / $\frac{1}{2}\rho U^2$.

some of these things which we know about it, more from the point of view of the practical man who has to use the information, than from that of the research worker who is studying it. For good and sufficient reasons, scientists wrap up their results in the form of diagrams involving coefficients, Reynolds numbers, and logarithmic scales; devices which, while admirable for conveying comprehensive information in condensed forms, are apt to obscure the practical issue for those who have no time to make a special study of the problem. My lecture will contain little or no information which has not been published in one form or another, but I hope that it may help those whose time for the study of these matters is strictly limited, to a clearer understanding of the nature of the "boundary layer," by which skin-friction is applied, and of the experimental technique by which it can be studied.

Skin-friction, of course, acts all over the exposed surface of an aeroplane; body, wings and controls, but I have entitled my lecture profile drag and will confine it to the skin-friction on the wings alone, because that is what we know most about at the present time. The ideas which I shall discuss are, however, applicable, with but little modification, to the drag of the body and other well streamlined parts.

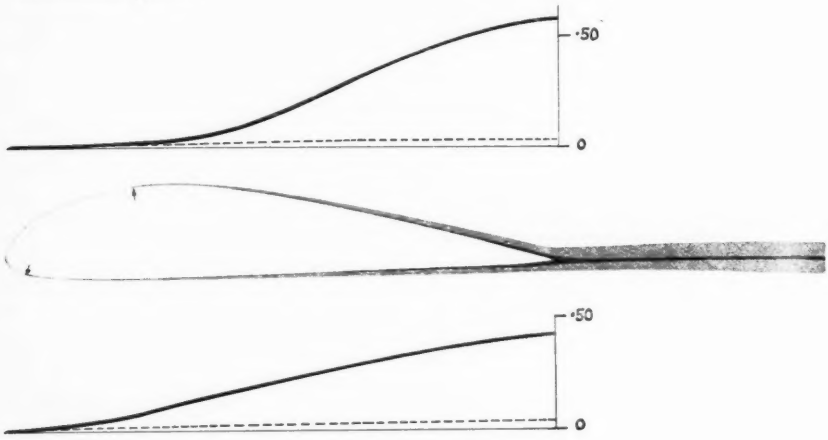


FIG. 1.

Pictorial representation of the boundary layer and wake of a wing in flight.

The thickness of the boundary layer and wake is represented, true to scale, by the black line and the shaded areas. Outside these areas total pressure loss is inappreciable and the flow is substantially that of an inviscid fluid. The inner edge of the black line defines the surface of the wing which is not otherwise represented. The outer edge defines what may be called the displacement thickness; the streamlines outside the boundary layer and wake are displaced as for a completely potential flow about this perimeter. The arrow heads indicate approximately the points of transition from laminar to turbulent flow in the particular experiment from which the figure was made. The thick curves above and below the wing show approximately the drag incurred in the boundary layer up to each point on the profile. The figure **0.50** indicates one half of the total profile drag of the wing. The broken curves represent roughly the skin-friction drags which would be incurred in an entirely laminar boundary layer.

THE BOUNDARY LAYER.

The ideal inviscid fluid imagined by mathematicians slips past solid surfaces with perfect ease and exerts no skin-friction. The real fluid, air, cannot slip in this way and its velocity must fall to zero as the solid surface is approached. The layer surrounding the solid boundaries of a stream, in which this velocity

fall takes place, is called the *Boundary Layer* and with large bodies of good streamline form moving fast it is relatively very thin. In calculating the distribution of pressure on the surface of such a body it is usual to ignore the boundary layer entirely and results obtained in this way are found to agree well with observation because, and only because, the boundary layer is thin. Skin-friction, of course, depends on what happens within the boundary layer and the necessary calculations relating to it become practicable only after the equations have been simplified by certain approximations which again depend on the layer being thin, so that it is perhaps worth while to begin by considering a scale representation of boundary layer of a typical wing in flight.

Fig. 1 shows the boundary layer and the wake which it creates for a wing with very smooth surface moving at about 84 m.p.h. ($C_L = 0.4$ Reynolds number $= 4.3 \times 10^6$). The information from which this figure is drawn comes from an experiment in flight by Stüper (1), in Germany, in which he used very small pitot tubes pushed gradually outwards through holes in the wing surfaces. The shape of the wing itself is defined by the clear space inside the boundary layer. The black and shaded regions indicate the extent of the boundary layer and of the wake which it produces. Outside the shaded area the flow is sensibly indistinguishable from that of an inviscid fluid, and the total-pressure has, as nearly as can be measured, the full constant value of the external stream. The black core within the shaded area shows what may be called the displacement thickness of the boundary layer; the streamlines outside the layer are substantially those appropriate to an ideal fluid flowing, without boundary layer, past a solid object having the form of the blackened region. The size of the black core gives, therefore, a pictorial idea of the errors which are incurred in calculating the flow outside the boundary layer on the asumption that the boundary layer does not exist.

The thick lines in the diagrams above and below the picture of the boundary layer, represent approximately* the amount of drag incurred up to any particular point on the wing profile, the scale being such that the mark against which is written the figure 0.5, represents half the total drag of the wing. It will be seen that the upper surface contributes the major part of the drag, because the local air speed there is higher than at the lower surface.

On both surfaces the thickness of the boundary layer and the amount of drag incurred in it remain very small for some distance from the front of the wing, and then begin to increase at a nearly uniform rate up to the trailing edge. The reason for this is that, in the thin forward part of the layer, the flow has what is called the laminar form; that is to say the separate sheets, or laminæ, of air overlying the solid surfaces slide one over another without mixing; when, however, the relatively rapid thickening begins, the flow within the layer becomes turbulent and there is a thorough mixing of the air from different levels. We shall have to consider the factors which determine the position of the point of transition from laminar to turbulent flow, but for the present we shall merely note that uncertainties in the location of this point are responsible for some of the chief difficulties in the experimental study of skin-friction drag. The broken line on each diagram represents approximately the drags which would have been incurred up to any given point of the profile, had the boundary layer over the whole wing retained the laminar form.

The Laminar Boundary Layer.

The form taken by the boundary layer depends to some extent upon the shape of the wing and is determined mainly by the distribution of pressure on the surface, but in its main features the layer about a wing of moderate thickness, or about a body of reasonably slim form, does not differ greatly from that

* Actually these curves represent the momentum-loss in the boundary layer, which is not exactly equal to the drag unless the pressure is that of the undisturbed stream. The difference, however, is unimportant in the present connection.

upon the surface of a flat plate. The simpler problem presented by the boundary layer on a flat plate has been extensively studied, both theoretically and experimentally, and a mathematical solution has been found which represents very accurately the layer in its laminar form.

Fig. 2 shows the form taken by the outside of the laminar layer, as deduced from this mathematical expression. In this diagram there are two scales; that on the right hand side represents the thickness of the layer in inches in a specified instance; that on the left has a more general meaning. In relation to the right hand scale, it must be supposed that the plate, shown diagrammatically in the figure, is 10ft. long in the direction of flow, and that air of standard density is moving over it at 200 m.p.h. The left-hand scale relates to any fluid, of any density, moving at any speed over a plate of any size, and shows amongst other things, that the higher the speed the thinner the layer; in fact the thickness of the layer in any position on the plate is inversely proportional to the square root of the speed. It is to be emphasised that this figure does not necessarily represent what *does* occur, on a flat plate, but what *would* occur if the layer were to retain the laminar form right to the trailing edge. Actually, on a 10ft. plate moving at 200 m.p.h., transition to the turbulent form would almost certainly occur in the layer somewhere in the forward half of the plate.

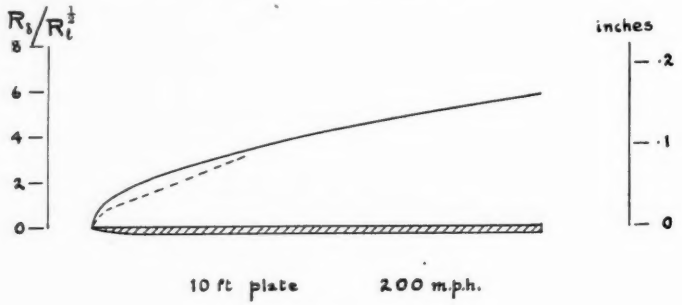


FIG. 2.

The thickness of the laminar boundary layer on a flat plate.

If the boundary layer were to retain the laminar form over the whole surface of a 10ft. flat plate moving at 200 m.p.h., the region in which there is appreciable reduction of air velocity would lie between the plate and the continuous parabolic curve, the height of which is shown on a greatly magnified scale. In fact, the layer would become turbulent over the rear part of the plate and in that part would therefore be much thicker than is here indicated. The short broken curve near the front of the plate indicates roughly the thickness of the laminar layer, when it occurs near the leading edge of a wing of moderate thickness at incidence appropriate to cruising speed. The scale of inches on the right-hand side relates to the size of plate and speed specified. The scale on the left-hand side is of universal application, R_δ and R_l being the Reynolds numbers formed from the boundary layer thickness and plate length respectively.

The thin broken line near the front of the plate in this figure shows, for comparison, the approximate thickness of the laminar layer over the forward part of a wing of moderate thickness, flying in an attitude appropriate to cruising speed. This line has been added merely to indicate the order of magnitude of the difference between the thickness of the boundary layer on the forward part of a wing and on a flat plate.

Fig. 3A shows what may be termed a velocity cross-section of the laminar layer, the horizontal lines representing the velocity of the air at various distances from the solid surface. The figure carries no scale because the cross-section has the same form at all positions on the plate. At any given speed the depth of the diagram must be supposed to increase in proportion to the square root of the distance from the leading edge and at any given distance from the leading edge to

decrease as the speed increases, in inverse proportion to the speed. It will be noted that the thickness of the layer cannot be precisely defined, because the velocity of the air approximates gradually to the velocity of the main stream; the short horizontal arrow marks, however, the point on the profile which was used in drawing the outer boundary of Fig. 2.

THE TURBULENT BOUNDARY LAYER.

Fig. 3B shows, for comparison with Fig. 3A, the distribution of mean velocity in the turbulent layer, the scales of the two diagrams having been so adjusted that each represents the same total momentum loss and therefore the same total incurred skin-friction. The broken lines towards the left of each diagram show the distribution of momentum loss at various points in the cross-section. The small thick arrow in Fig. 3B indicates the point on the cross-section which will be used in later figures to define the thickness of the turbulent layer in various circumstances.

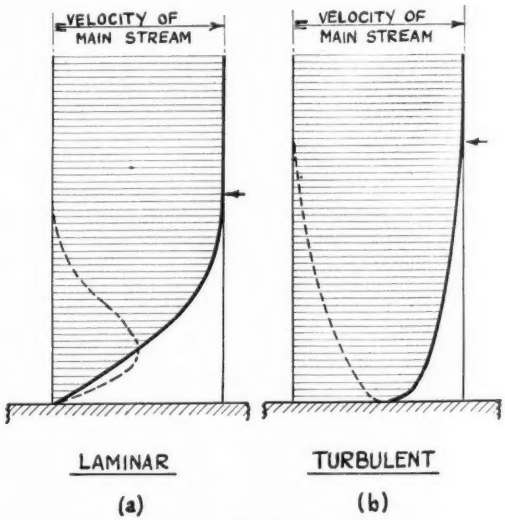


FIG. 3.

Velocity distribution in the cross-sections of the laminar and turbulent boundary layers.

On a flat plate the form of the velocity cross-section of the laminar layer is the same in all positions, but the depth of the layer increases with the square root of the distance from the leading edge. To fit this curve into Fig 2 the vertical scale must be adjusted until the short arrow coincides with the continuous parabolic curve. The form of the velocity cross-section of the turbulent layer changes slightly with change of Reynolds number, but Fig. 3b represents it approximately at Reynolds numbers appropriate to aeroplane wings. The broken curves show the distribution of momentum loss in the cross-section, and the scales of the two figures are adjusted so that each represents the same total loss of momentum, which is equal to the total drag incurred on the surface in front of the cross-section in question.

In Fig. 4A, Fig. 3B is reproduced to a different scale to represent the velocity cross-section of the turbulent layer near the rear edge of a flat 10ft. plate moving through air at 200 m.p.h. In this figure I have attempted to give a pictorial representation of the fact that the turbulence gradually dies out with increasing distance from the surface of the plate, until, when the full velocity of the stream outside the layer is realised, the flow becomes uniform. On the scale of Fig. 4A

the velocity at the surface of the plate appears to be about half that of the main stream, but we know from physical considerations that at the surface of the plate itself the velocity of the air relative to the plate must be sensibly indistinguishable from zero.

THE VISCOUS SUB-LAYER.

What does in fact happen near the surface of the plate is shown in Fig. 4B, where the region very close to the surface is shown magnified to a scale 100 times greater than that used in Fig. 4A. From this figure it appears that the last third of the fall of velocity takes place very rapidly in about the last one-thousandth of an inch, and I have again indicated, pictorially, the

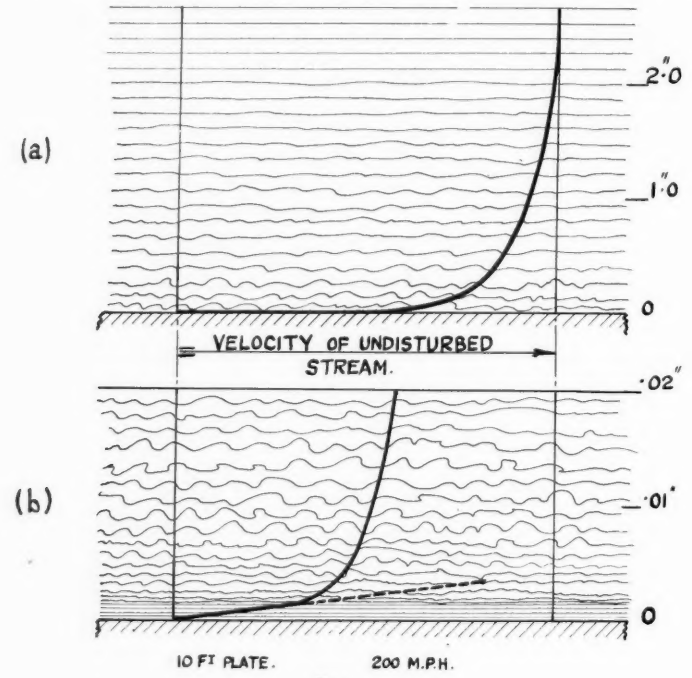


FIG. 4.

Velocity distribution in the cross-section of the turbulent boundary layer with pictorial representation of regions of turbulence.

These curves represent the turbulent boundary layer at about 10ft. from the front of a flat plate moving at 200 m.p.h. They show pictorially the distribution of turbulence, but no significance is to be attached to the shapes of the lines by which turbulence is indicated. In Fig. 4b the vertical scale is increased in order to show the viscous sub-layer in which turbulence is small and mean velocity nearly proportional to distance from the solid surface.

fact that in this region the turbulence dies away, so that there is, beneath the turbulent boundary layer, an exceedingly thin viscous sub-layer, as it may be called, within which the velocity gradient is very great and the flow returns nearly to the laminar form. It is this large velocity gradient, occurring very close to the plate, which applies the skin-friction to the solid surface, and when we remember that the shearing force in viscous flow is proportional to the velocity gradient, we realise how the turbulent boundary layer can apply a skin-friction

force many times greater than that of the corresponding wholly laminar layer, although the overall thickness of the latter may be much less.

The discovery of the viscous sub-layer beneath the turbulent layer has proved of the greatest importance to the understanding of skin-friction, because it appears that, provided the roughness on the surface over which the air flows does not protrude beyond the viscous sub-layer, it has no effect upon the turbulent outer parts of the layer through which the drag is conveyed from the main stream, and hence it has no effect upon the skin-friction.

Aerodynamically Smooth Surfaces.

It is from these considerations that we now have the well-known conception of an *aerodynamically smooth* surface; that is to say of a surface which, though not absolutely smooth, behaves in respect of skin-friction as though it were absolutely smooth. When a surface is not aerodynamically smooth and the projections on it penetrate through the viscous sub-layer, the effective depth of the main turbulent layer is increased, and with it the skin-friction.

It is not, of course, possible to give an exact figure for the thickness of the viscous sub-layer, because the viscous flow merges gradually into the overlying

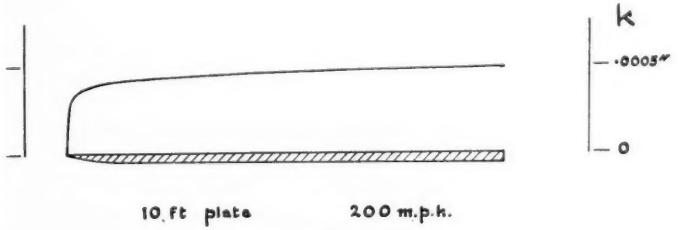


Fig. 5.

Permissible roughness on an aerodynamically smooth plate.

Roughness formed by small closely distributed particles adhering to the plate does not influence skin-friction provided that at any distance behind the leading edge the diameters (k) of the particles are less than is indicated in the figure. For practical purposes it is sufficient to assume the same value for permissible roughness at all points on the plate, although theoretically permissible roughness falls to zero at the leading edge.

turbulent flow; for the same reason it is not possible to give an exact figure which will, in any given circumstances, divide an aerodynamically rough surface from one that is aerodynamically smooth. But although no such exact definition can be made, it is possible, as a result of a beautiful series of experiments made by Dr. Nikuradse,* under the direction of Professor Prandtl, to define a scale of roughness which will give an indication of the dividing line between the two régimes. We may then say that not until the roughness is appreciably greater than that defined in this way will any important increase of skin-friction become apparent.

From the above-mentioned experiments it is possible to deduce a very simple formula to indicate this limiting roughness when the air has the density and temperature appropriate to ground level. This can be written:—

$$1/k = 200\, U_m \sqrt{C_f}.$$

where k represents the scale of the roughness in inches, U_m the speed in m.p.h., and C_f the local skin-friction coefficient for a smooth surface (friction per unit area)/$\frac{1}{2}\rho U^2$. If the roughness is on a scale appreciably less than is given by

* An account in English of these experiments and deductions from them is given by Prandtl in Vol. 3 of "Aerodynamic Theory." Edited by W. F. Durand, published by Julius Springer.

this expression, no further smoothing of the surface will reduce drag, but if the scale of the roughness is increased beyond this value the skin-friction will increase, at first slowly and later more rapidly; thus, when the roughness scale is increased to twice the above value the skin-friction will be increased by about 5 per cent., but if the roughness scale is increased ten times the skin-friction will be increased by about 40 per cent.

Fig. 5 shows the variations of k across a 10ft. plate at 200 m.p.h., as given by the above formula, and from this figure it appears that although the value of k falls, theoretically to zero, at the leading edge itself, in practice, when we take into consideration the rather vague meaning of k, it is amply sufficient to assume that it has a constant value appropriate, say, to the middle of the plate.

The value of the coefficient C_f varies with the size of the plate or wing, and with the air speed, but within the range of values appropriate to aeroplane flight, the variation of C_f is not large, and, of course, the variation of $\sqrt{C_f}$ is still less. Again remembering how indefinite is the meaning of k, it is sufficiently accurate for most practical purposes to give to C_f in this expression a mean value, in round numbers say 0.003, so that the expression reduces approximately to:—

$$1/k = 10\ U_m.$$

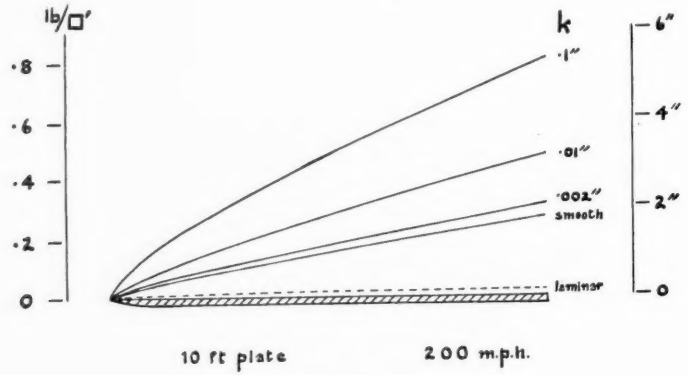


FIG. 6.

Thickness and drag of the turbulent boundary layer in various circumstances.

The point on the velocity cross-section of the turbulent boundary layer which has been selected to define its thickness in this figure is shown by the arrow in Fig. 3b. Referred to the right-hand scale the curves show the thickness of the turbulent layer at any point on the plate, when the roughness of the surface is defined by the dimension k, as described in Fig. 5, and when turbulence starts very near the leading edge. Referred to the left-hand scale the curves represent approximately the drag incurred between the leading edge and any given point on the surface. The dotted line represents the thickness which the laminar layer would have if it could extend over the whole plate. The left-hand drag scale does not apply to the dotted curve.

Thus, a plate moving at 200 m.p.h. near the ground can be regarded as aerodynamically smooth if the projections upon its surface are less than about half of one-thousandth of an inch, but if it were to move at 400 m.p.h. it would not become aerodynamically smooth until the projections were reduced to half this value. At great heights the permissible roughness of an aerodynamically smooth surface increases, the value at any given true speed being roughly doubled at 30,000ft., quadrupled at 45,000ft. and increased six times at 55,000ft. At any given height, however, it may, for practical purposes, be taken to depend only on the velocity of the air passing over the surface. This local velocity, it

must be remembered, may be greater at some parts of a wing or body than the velocity of the body itself through the undisturbed air.

The numerical values quoted above as defining permissible roughness have been deduced from experiments upon a particular form of roughness in which the surface was covered with small approximately spherical particles lying close together and made to stick by some form of varnish. The length k is to be interpreted as the diameter of these particles. With roughness projections of different character, the values of k for aerodynamic smoothness would be different. Some experimental evidence of the value of k with different kinds of roughness is contained in reference (2).

TYPICAL VALUES OF SKIN-FRICTION AND BOUNDARY LAYER THICKNESS.

Fig. 6 shows the thickness of the boundary layer at various points across the 10ft. plate at 200 m.p.h., when the surface is aerodynamically smooth and when

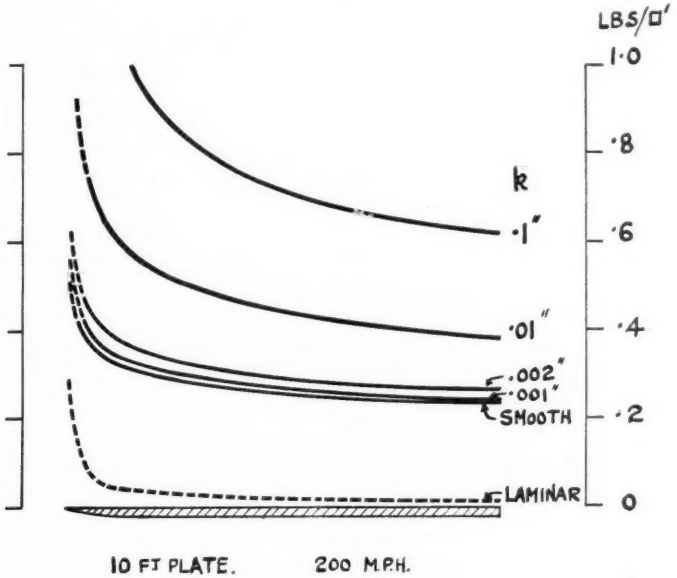


FIG. 7.

Distribution of skin-friction in the turbulent boundary layer.

These curves show the distribution of the local intensity of the skin-friction corresponding to the curves of thickness and total skin-friction in Fig. 6. Although theoretically the intensity of skin-friction rises indefinitely towards the leading edge, it is for many purposes sufficiently accurate to assume a constant skin-friction over the whole surface.

its roughness is defined by various values of k. From Fig. 3B it is clear that, as with the laminar layer, the thickness of the turbulent layer cannot be very clearly defined, but the same convention has been adopted for all the curves in Fig. 6, the position of the point chosen to define the outer limit of the layer being shown by the arrow in Fig. 3B. The thickness of the laminar layer, could it exist in these circumstances, is shown in Fig. 6 by a broken line.

It happens that the total drag incurred up to any point on the plate is nearly proportional to the thickness of the turbulent boundary layer at that point, and on the left-hand side of the diagram is a scale by reference to which the curves

give approximately the total drag incurred up to each point on the plate. This drag is expressed in terms of pounds per square foot of total wing area.

Fig. 7 shows the distribution of local skin-friction corresponding to the total skin-friction curves in Fig. 6. With an ideally sharp leading edge the intensity of skin-friction rises indefinitely as the leading edge is approached, but that this does not imply an infinite force on the plate can be inferred from Fig. 6, and since no real plate can be infinitely sharp, the curves are shown as broken lines near the leading edge, to indicate that the sudden rise has little practical significance.

Fig. 8 shows the total skin-friction on the flat plate plotted against k. It will be observed that, although in these circumstances the limiting value for aerodynamic smoothness has been given as 0.0005 inches, the rapid rise in drag does not begin until k exceeds 0.001 inches.

THE POINT OF TRANSITION TO TURBULENT FLOW.

We have next to consider the factors which determine the point at which the boundary layer changes from the laminar to the turbulent form. Numerous attempts have been made to find some theoretical limit beyond which the laminar

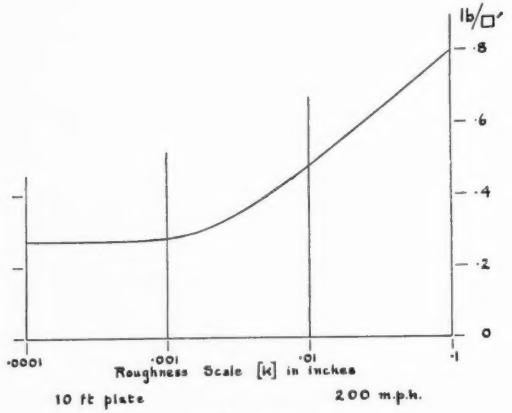


FIG. 8.

Mean skin-friction on a flat plate for various degrees of surface roughness.

The quantity k in this figure defines the scale of the roughness as described in Fig. 5. The limiting value for an aerodynamically smooth plate at 200 m.p.h. is given in the text as .0005 inch, but this figure shows that not until k is considerably greater than this is any large increase of skin-friction incurred.

boundary layer becomes unstable to infinitesimally small disturbances, but the most generally accepted opinion now seems to be that there is no such point. Though it has not yet been definitely established, it seems that a finite disturbance is always necessary to cause turbulence to start developing, but that the magnitude of the disturbance which is able to do this becomes less and less as the layer grows thicker and thicker.

Imagine an unsharpened lead pencil, standing on end on a flat table. A small but finite push will be required to upset it, but if the push exceeds a certain strength it will fall right over. Suppose now that the pencil has been partially sharpened, so as to reduce the area of the flat base on which it stands; a smaller push will now upset it, and if the sharpening is carried almost to a point,

the pencil, though theoretically capable of standing on an absolutely horizontal table in a perfectly still room, will in practice be impossibly difficult to balance. Imagine an experimenter trying to determine how far the pencil can be sharpened before it becomes impracticable to make it stand up permanently in any given surroundings and you have an idea of the kind of problem involved in defining the transition point in the boundary layer; for, as the laminar layer grows in thickness with increasing distance from the leading edge, it becomes more and more easily upset by disturbances impressed upon it from without by irregularities in the external air stream, or generated from within by irregularities of the surface over which it is formed. To complete the analogy, suppose that the majority of experiments on the pencil have to be made in an industrial area where the table is subject to small and not easily defined vibrations, whereas the result is required to apply in the depth of the country where external vibrations are almost non-existent. The air stream of the wind tunnel, in which boundary layer experiments are mainly carried on, contains small and not easily

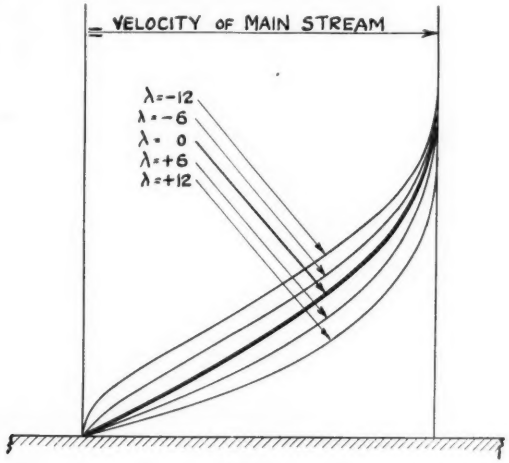


FIG. 9.

Velocity cross-sections of the laminar boundary layer when the pressure gradient in the direction of flow has various values.

The dimensionless quantity λ is defined in the footnote on page 350. It is positive when pressure is falling in the direction of flow and negative when pressure is rising. It is generally believed that negative values of λ favour transition to the turbulent form of the boundary layer and positive values postpone transition. If the layer remains laminar until λ reaches the value -12 the main stream separates from the solid surface. These curves are drawn according to Polhausen's assumption that the cross-section can be expressed as a quartic curve with curvature at the origin appropriate to the value of λ. The assumption is approximate only.

defined irregularities, whereas the open air through which aeroplanes fly seems to be remarkably free from the relevant type of disturbance.

In the relatively simple conditions which obtain on a flat plate, we know from theoretical considerations that the sensitivity of the layer to outside disturbance must depend on what is called the Reynolds number of its thickness; that is to say, upon the quantity $\delta U/\nu$ where δ is the thickness of the layer, U the velocity of the air outside it, and ν is a property of the air called its kinematic viscosity, the value of which increases at great heights, but for present purposes may be regarded as constant. When this quantity, which is generally given the symbol R_δ, reaches a value in the neighbourhood of 4,000—on our plate at

200 m.p.h. this would happen between 3 and 4 inches from the leading edge—the turbulence found in many wind tunnels is sufficient to cause transition to occur, but wind tunnel experiments have been reported in which transition was postponed to much larger values of R_δ (3) and no one yet knows to what values it could be postponed on a very smooth plate moving very steadily through very calm air.

On a wing the factors which determine transition are more complicated than on a flat plate, because the sensitivity of the layer to outside disturbances depends not only upon its thickness but also upon the pressure gradient outside it, which varies from point to point along the wing profile.

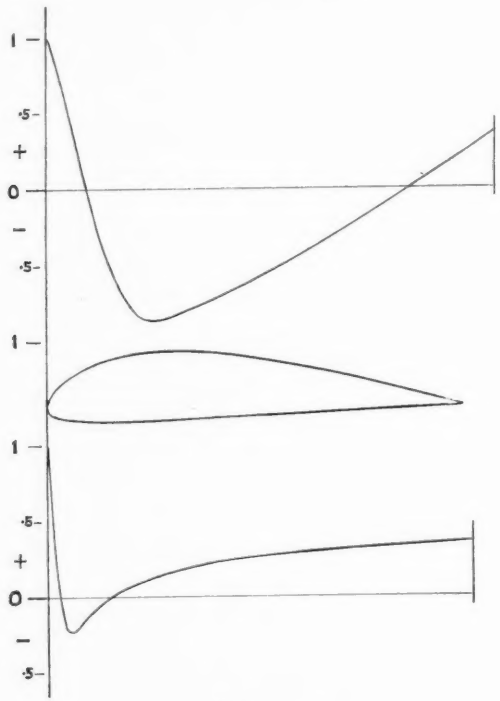


FIG. 10.

Pressure distribution on a wing.

The abscissæ in the pressure distribution diagrams represent distances backwards along the wing profile, starting from the point where the stream divides on the leading edge. On both surfaces pressure at first falls in the direction of flow (λ positive) and then rises again (λ negative), the rise being sharper on the lower surface. It is these rising gradients which are supposed to increase the difficulty of making the laminar layer extend over a large part of the wing surface.

Fig. 9 shows what are called Polhausen's approximations to the cross-section of the laminar boundary layer when the pressure gradient outside it has various values. The quantity* λ, which appears on this figure, is the conventional

* $\lambda = \dfrac{\delta^2}{\nu}\dfrac{dU}{dx}$ or $-\dfrac{\delta U}{\nu}\cdot\tfrac{1}{6}\delta\dfrac{d(C_p)}{dx}$

where x is distance along the boundary in the direction of flow, δ is the thickness of the boundary layer, ν is the kinematic viscosity and C_p is the pressure coefficient.

dimensionless coefficient used to represent this pressure gradient; it is positive when pressure is decreasing in the direction of flow and negative when pressure is increasing. When λ is zero the pressure outside the layer is uniform and its cross-section is identical in form with that of Fig. 3A. When λ is positive the cross-section of the layer takes a form which is supposed, on theoretical grounds, to be less sensitive to external disturbances, and when λ is negative the form taken is supposed to become more sensitive. Thus, a falling pressure in the direction of flow is expected to postpone transition and a rising pressure to encourage it.

One of the problems engaging the attention of experimenters at the present time is to find relations between R_δ and λ at the points where transition occurs in any given circumstances. At Cambridge we are working on this problem, but are not sufficiently advanced to say more than that we are finding transition in flight postponed to larger values of R_δ than are usual in wind tunnels. Using a very smooth wing surface we have, for example, found transition occurring on the upper surface as far back as twenty inches from the leading edge, when the air speed is well over 200 m.p.h. and λ has a slight negative value, but the layer is then in a very sensitive condition. For example, a transverse ridge near the leading edge of one one-hundredth of an inch in height brings the transition point right forward, whilst a ridge so small as one five-hundredth of an inch will cause it to move forward by a few inches.

Fig. 10 shows the pressure distribution on the wing used by Stüper of which the boundary layer is illustrated in Fig. 1. Near the front, on both upper and lower surfaces, the pressure is falling rapidly in the direction of flow, so that here the boundary layer is expected to be less sensitive than in the corresponding position on a flat plate. But some little distance behind the leading edge the pressure on both surfaces passes through a minimum value and then begins to rise again and here one expects the layer to be more sensitive than on a flat plate. The comparatively sharp pressure rise occurring very near the front on the lower surface probably accounts for the relatively early transition actually observed by Stüper on that surface.

Discussion.

I hope that by this brief sketch of a rather complicated matter I have been able to convey, at least, some general idea of the nature of the problem confronting those who are trying to reach a clearer understanding of the factors which control profile drag, and indeed of the skin-friction drag of all parts of the aeroplane. For obvious reasons we all want to know the minimum figure to which it is possible to reduce the drag of large wings of various thicknesses flying at high speeds, and I have tried to make it clear that a firm answer to this question cannot be given from wind tunnel experiments alone, and that even observation of drag made in actual flight cannot be completely interpreted until we know more than we know at present about where the boundary layer passes from laminar to turbulent form.

It must not be deduced from these remarks that wind tunnel observations of drag are of no further value. On the contrary, without the numerous observations which can be obtained with comparative ease in wind tunnels, but little progress could be made towards a general understanding of a problem of this kind. It is the function of flight experiments to provide the final check and what might be described as the key to the correct interpretation of the much greater quantity of detailed information obtainable from the tunnels; the flight experiments in any general research should always be carefully chosen with this end in view. It may, for example, be found that with very large wings, travelling very fast, there is no hope of making the laminar layer extend over an appreciable portion of the surface; in which case, wind tunnel experiments in large tunnels, or in the compressed air tunnel, would probably give entirely

reliable results. On the other hand, it may not be so, and the wind tunnels may give higher estimates of drag than will actually be realised; it is not impossible that they may even fail to give correctly the comparative figures for wings of different thickness. Next year's research should settle the point fairly definitely.

Again, I am anxious not to give the impression that startling drag reductions can easily be realised by coaxing the boundary layer to remain laminar. If this could be done over the whole wing the results would be startling enough, but the indications are that it is improbable that the laminar layer can be made to extend over more than about one-third of the whole wing surface, which would involve a decrease of drag of the order 20 per cent. in comparison with a wing upon which the layer is entirely turbulent. Even this, it must be remembered, applies in all probability only to those parts of the wing which do not lie in the slip-stream of the screws.

Drag Measurement with Exploring Pitot.

The experimental methods by which it is now possible to measure in flight the profile drag of a wing or of any part of it, and to locate the point of transition from laminar to turbulent flow in the boundary layer are of some interest. In the past the only available method was to measure the drag of the whole aeroplane

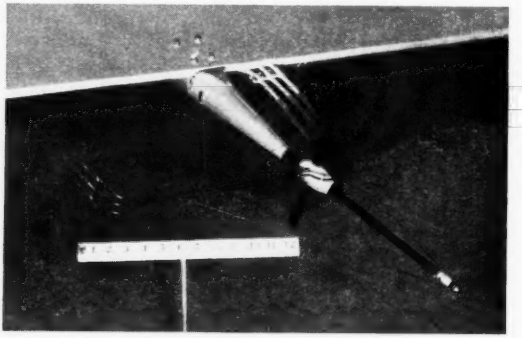


Fig. 11.

Apparatus for traversing exploring pitots across the wake of a wing.

This figure shows one arrangement for measuring profile drag by the pitot traverse method. Two small pitot tubes, with a small static pressure tube between them, can be moved across the wake by an electric motor which slowly rotates the bracket on which they are carried about an axis which coincides with that of the conical fairing shown on the trailing edge of the wing in the figure. From measurements of pressures in these tubes the profile drag coefficient for the portion of the wing in front of them can be calculated with good accuracy.

and there was no certain way of separating out the drags of the various parts and allowing accurately for interference between them. The modern method of measuring profile drag depends on the fact that the pressure in a pitot tube has, very accurately, a constant value at all points in the flow, except in boundary layers or in the wakes which they create. Since, without a wake, no profile drag is possible, it follows, without further reference to theory, that an exploring pitot tube can be used as a very delicate indicator of the presence of drag. It is only necessary to connect the exploring pitot, which may be very small, through a sensitive pressure-gauge, to a fixed pitot situated well away from any wake or boundary layer, and to search for regions in the flow where the gauge reading

deviates from zero. For any such deviation indicates certainly that somewhere in front of the exploring pitot is an object experiencing drag. The uses to which such a device can be put for detecting places, as for example near the wing roots, where there may be unexpectedly high drags, are obvious, but in certain circumstances the measured pressure drops can be used not only to detect drag, but to give a remarkably accurate measure of its magnitude.

The easiest measurement to make in flight by these means is probably that of the local profile drag of any given portion of a wing, for this involves only a single traverse of the exploring pitot across the wake, whereas to measure the drag, say, of a body near the wing roots, involves a complete exploration of the wake in three dimensions.

This method of the exploring pitot was, I believe, first employed for measuring profile drag in flight by M. Schrenk, reference (4), in Germany, in 1928, but Schrenk unfortunately died shortly afterwards and, so far as I am aware, the method was not used again for this purpose until we started to develop it at Cambridge about two years ago. The details of our experiments are fully described in reference (5), and the results may be summarised by the statement that the exploring pitots can be situated as closely as is convenient behind the wing and can be so light and small that they are easily attached to the trailing edge, without structural alteration to the aeroplane. The pressures in the pitot tubes can be recorded very easily in flight and from them profile drag can be deduced by a simple calculation with an accuracy for comparative purposes of the order 2 per cent.

The absolute accuracy of the method is not yet known for certain, but it is thought to be of the same order. It is at present being investigated by a rather elaborate experiment in one of the larger wind tunnels at N.P.L. Here, numerous traverses will be made behind an isolated wing of elliptic plan form, and the drag deduced from them will be compared with the measured drag, after the appropriate allowance has been made for induced drag. The form taken by the exploring pitot in our recent experiments at Cambridge is shown in Fig. 11.

An alternative plan, which is in some ways more convenient, is to replace the single or double travelling pitot by a " comb " consisting of several pitot tubes fixed in a plane crossing the wake. This method requires more connecting tubes between the measurement station and the manometer in the cabin, and the manometer has to be more elaborate, but it avoids the necessity of moving the pitot on the wing through accurately known distances, and it enables observations in flight to be made more rapidly. The comb method has been developed by R.A.E. into a routine and is being used to study the profile drag of wings of various thickness and surface roughness.

Locating the Transition Point.

Though the profile drag itself is what we require to know for practical purposes, we have seen why its variations will be difficult to understand, unless we also know in each instance the position, on the wing profile, of the point of transition from laminar to turbulent flow. This point, fortunately, is also easily determined by the use of an exploring pitot. Figs. 12, 13 and 14 show an arrangement which we are using at Cambridge for this purpose. It consists of a group of three very small tubes, about one-twentieth of an inch external diameter, two of which are open ended to form pitot tubes, and one closed with small lateral holes to form a static-pressure tube. The whole can be pushed forwards or backwards along the wing profile, and the pitot nearest to the wing is just sufficiently far from it to be clear of the boundary layer so long as it remains in the laminar form. After transition to the turbulent form the layer thickens rapidly so that, as the pitot is withdrawn along the wing profile, it passes into a region of reduced total pressure very soon after it has passed the transition point.

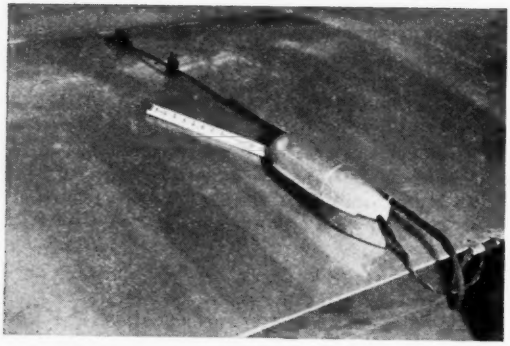


FIG. 12.

FIG. 13.

FIG. 14.

Three views of an apparatus for locating the point of transition from laminar to turbulent flow.

An electric motor enclosed in the fairing shown in Fig. 12 slowly pushes forward the group of small tubes shown more clearly in Figs. 13 and 14. Two of these are pitot tubes situated about 2 mm. and 4 mm. respectively from the wing surface and one is a static-pressure tube about 6 mm. from the surface. When the pitot tubes are above the laminar layer they give the full total head of the stream, but soon after they have been withdrawn behind the transition point they pass successively into the rapidly thickening turbulent layer and register a fall of total pressure. The static-pressure tube gives approximately the distribution of static pressure over the wing surface.

The second pitot is situated farther from the surface and does not register any fall of pressure until it has been withdrawn sufficiently far behind the point of transition for the turbulent layer to have thickened considerably. Its purpose is to check that the fall of pressure in the inner pitot was really due to the onset of turbulence and not to some unsuspected slight thickening of the laminar layer itself. By the use of this arrangement it is possible to locate the transition point within about one inch, which is an accuracy sufficient for practical purposes. The static-pressure tube which accompanies the pitots is unnecessary for the location of the transition point, but it gives a good approximation to the pressure distribution on the wing surface, which, for research purposes, is required for correlation with the transition.

Profile Drag Values.

I have confined this lecture to the problems involved in the study of profile drag, and have made no mention, except in passing, of the actual values observed. Information of this kind is now coming in rapidly, but it is too soon to discuss it in detail. Figures are published from time to time as soon as they are reasonably definite, but the existing information has not yet been sufficiently correlated to make public discussion worth while. It is, however, worth mentioning that when, as in a recent report of ours (5), the profile drag of a wing is found to agree almost exactly with the accepted figure for the drag of the equivalent flat plate with completely turbulent boundary layer, it must not be inferred that the boundary layer is therefore turbulent all over the wing, or that there will be the same agreement with the flat plate figures in all circumstances. It now appears that the drag of a wing with entirely turbulent boundary layer is appreciably greater than that of the equivalent flat plate, partly because the local velocities over its surface are higher than in the undisturbed stream, and partly, it may be, because there is a small form drag. When agreement with flat plate figures is observed it can only be due to a coincidence; the reduction of drag consequent upon a part of the layer being in the laminar state cancelling the increases from the above causes. With our wing, for example, the layer on the upper surface is known to have been laminar for nearly one-third of the chord from the leading edge, and when we forced it to become turbulent by adding, near the leading edge, a transverse ridge one-hundredth of an inch thick, the drag rose by about 10 per cent.

Wind tunnel observations show drag coefficients departing in the upward direction from the flat plate values by amounts which increase with Reynolds number, and if, as is probable, this should prove to be due to a forward movement of the transition point, it may not occur in flight, though it will certainly become more and more difficult to prevent it from occurring as size and speed increase. It may, on the other hand, as we have seen, be due to surface roughness affecting the turbulent part of the layer more at high speeds than at low speeds, in which case the corresponding rise of drag would certainly occur in flight unless the wing were relatively smoother than the model. The problem presented by the drag of a wing in flight is thus very complicated, and even so apparently simple a matter as the effect of roughness cannot be completely analysed unless it is realised that it presents two distinct problems: the effects of roughness on the point of transition of the boundary layer to the turbulent form, and its effects on the skin-friction applied by the turbulent boundary layer.

Simplicity of the Method of the Exploring Pitot.

One point which I wish to emphasise before I conclude is that the method of the exploring pitot, which is capable of providing the answers to the questions we have been discussing, is peculiarly suitable for use by constructing and operating firms, who cannot afford to allocate their newer types of aeroplanes to long courses of research involving structural alterations. Properly developed,

the method can be quickly and easily applied to any aeroplane, and will give useful results with relatively small expenditure of flying time. It provides what is probably the only practicable way of accurately measuring the effects of changes of surface finish at speeds higher than are available in wind tunnels and it can be extended, possibly with lower accuracy, to locate sources of drag other than the profile drag of the wings. To my mind the problem of reducing drag to the lowest possible figure is rapidly passing into the stage in which it can best be studied by detailed examination of each successive type and modification as it appears, and it should therefore become more and more the concern of the firms themselves, who can prosecute it with reference to the particular designs which they favour.

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Discussion.

The President: He recalled a lecture delivered by Professor Melvill Jones seven years ago on the streamlined aeroplane, in which he had drawn up a kind of ideal standard to which machines could conceivably theoretically attain. A little while before that lecture was delivered, Mr. Tizard (who had since become Chairman of the Aeronautical Research Committee) had suggested to him, the President, that it would be a very good thing if there were for the aeroplane some sort of ideal, such as that which existed, for instance, in the " air standard " of efficiency for the internal combustion engine. Professor Melvill Jones, in the lecture referred to, had provided what was wanted. It had had a very big influence throughout the world in focussing attention upon the desirability, and possibility, of attaining a much greater degree of streamlining than had been customary. In the intervening years great progress had been made. Professor Melvill Jones had shown, first by the wool tuft method, which parts of aeroplanes were not properly streamlined and where interference occurred; secondly, he had shown how the wake method originated by Schrenk, in Germany —but not much applied there, seemingly—for the measurement of drag could be used as a practical every-day tool. This enabled those who were doing full-scale experiments to measure the drag of a wing, not by subtracting one performance measurement from another, carried out possibly on different days and under slightly different conditions, but by direct measurement. The method had the enormous convenience that when experimenting on a wing one need not treat the whole wing, but only a space about 3ft. wide and work by measurements in the wake of that narrow width. The President expressed the hope that in the course of the discussion the aircraft constructors would express their views about the method and how far they considered they could adopt it.

The President was much impressed by the illustration, in Fig. 1 of the paper, of the laminar layer and the turbulent layer. He likened the laminar layer to a sheet covering the wing or body and the turbulent layer to a blanket outside it, both of them becoming rather thicker towards the foot of the bed.

Dr. Douglas (*Fellow*): He expresed his admiration and gratitude to Professor Melvill Jones for his exceedingly valuable work on the measurement of surface drag, which was a difficult and critical business at high flight speeds. The drag of a wing, he said, depended critically on the position of the transition

point, and at really high speeds on large chord wings the position was exceedingly sensitive even to very minor changes. At Farnborough, for instance, it was found that with a very smooth wing—it was made so smooth that the total resistance was down to that of turbulent skin friction—a little moisture or mist forming on the leading edge increased the drag by 20 per cent.; very minor changes of surface and waviness on the first third could produce very large changes in the drag.

Responding to the President's invitation to deal with the fixed comb pitot tube method as used at Farnborough, Dr. Douglas said that the comb was fixed rigidly at about 1/10th of the chord behind the trailing edge. The tubes were led to a series of manometer tubes in the cockpit of the machine and photographic records were taken. By taking suitable precautions—it was necessary to be very careful about leaks—very consistent results were being obtained.

Bearing in mind what the author had shown to be possible on the upper surface of the wing, Dr. Douglas asked if he had considered how far, by varying the profile, he could get the laminar layer to move back on the lower surface.

Mr. J. E. SERBY: He had been concerned with the experiments at Farnborough, and the fixed comb pitot was used there because it was felt that it would save time. A number of tests were being carried out on the same wing, and obviously the ability to take one complete record of the drag at a given speed with one shot of the camera did save time and perhaps added a little to the accuracy.

Discussing the suggestion by the author that the aircraft constructors could carry out on their latest aircraft some tests similar to those described in the paper, Mr. Serby said it was useful research for the author and for those engaged in experiments at Farnborough to fit a really smooth polished skin over a wing and to measure the drag under those conditions, but probably the unfortunate designers felt that such experiments would not be of very much immediate value to them. One imagined that they would like to know exactly how much the drag of the wing was increased by inspection panels, slight bumps in the jointing of the wing covering, and so on. If they could carry out the tests on their own aircraft—after all, they had access to the fastest aircraft in the country—and if the apparatus could be simplified still further, they would find it extremely valuable. The comb had to be fixed to the wing very securely, of course, but Mr. Serby did not think that that presented insuperable difficulty. The practice at Farnborough was to take photographs of a manometer connected to the pitots, but possibly the measurement could be made more convenient by substituting air speed indicators for the liquid columns of the manometer. It should be borne in mind, in that connection, that the most important experiments would probably have to be done on single-seater aircraft, since they combined fairly clean wing design with high speed, so that there would be no observer present, and the pilot, using the apparatus at present applied at Farnborough, would have to operate the camera and watch the manometer. However, the problem was not insuperable. The constructors would be able to make the first experiments at the highest available Reynolds numbers. Although the author had given the Reynolds number only a " walking on " part, one felt that when the Reynolds number was not " walking on " it was doing the work of stage manager off stage and was a very important factor all the time! The sooner the constructors themselves could get busy by experimenting at the higher Reynolds numbers the better.

These wake experiments he had found very fascinating, and to watch the wake develop as speed increased, as indicated on the manometer, was extraordinarily interesting; from the moment the machine gathered speed as it ran across the ground one could watch the wake developing. The experiments at Farnborough had produced some interesting illustrations of how a small amount of moisture on the wing increased the drag; on one occasion the machine in which the tests were made had run into a mist which had deposited fine drops of water on the

wing and the drag had increased at once by some 20 per cent. A much greater increase resulted from the collection of a small amount of ice on the wing.

Dr. F. W. LANCHESTER (*Hon. F.R.Ae.S.*): He began by illustrating the form of flow past a sphere, and recalled Prandtl's experiment in which a wire ring was soldered to a sphere, the effect of which was to set up turbulence, this causing the stream to cling to the surface and prevent "break away," so reducing the resistance of the sphere to about half its original value. He suggested that possibly the extension of the condition of laminar flow might have the reverse effect and result in reducing the maximum lift by inducing an earlier burbling condition. Dr. Lanchester added that he had mentioned this point in the paper he had read before the Society in November.

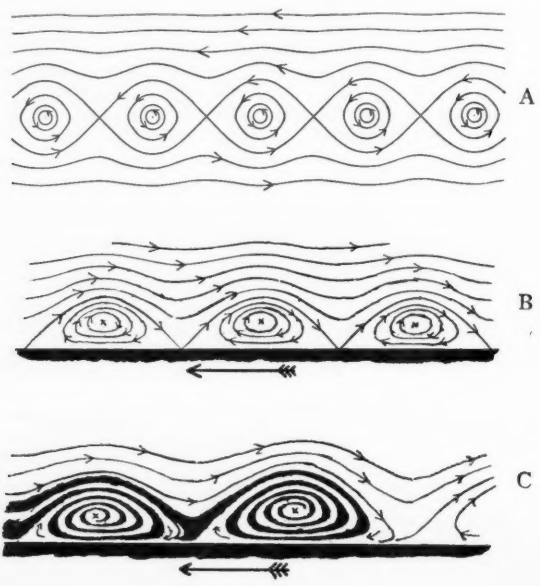
Discussing the skin friction diagram and referring to Fig. 2 from his paper, he asked whether the 1.5 in the expression $R = V^{1.5}$ was accepted by Professor Jones. He understood that that condition, at extreme low Reynolds numbers, was generally agreed.

Another question was whether Professor Melvill Jones had considered the proposition that the minimum value of drag corresponded to the condition when the direct resistance was equal to the aerodynamic resistance or induced drag. If that proposition were true, he did not think that they were justified in dismissing induced drag as unimportant. (Dr. Lanchester here referred to Figs. 9 and 10 of his previous paper.)

Next, referring to Fig. 12 (Fig. 3 from R. and M. 1627), Dr. Lanchester said that the breakaway from the theoretical curve indicated that as the Reynolds number became lower, the burble point became earlier. That rather confirmed the conclusion that any attempt to delay the onset of turbulence might result in an earlier burble condition and give rise to loss of lift and to inefficiency such as witnessed for low values of N_R.

The small rib which Professor Melvill Jones had mentioned might, by increasing turbulence, be of advantage from the point of view of delaying "burble," as in the case of the Prandtl sphere.

Dr. Lanchester then exhibited slides showing the manner in which vortices suffered degeneration, being Figs. 22 and 23 from his paper "The Aerofoil in



the Light of Theory and Experiment " (Inst. A.E., 1915), and suggested that there might be a stage in the development of turbulence in the phenomenon of skin-friction, analogous to the break up of the Helmholtz " vortex sheet " when a surface of discontinuity arises in a free fluid. This is illustrated in Fig. A (from " Aerodynamics," p. 136), the vortex sheet originating as a surface of kinetic discontinuity becomes the seat of true vortex motion of the type depicted, but this being unstable cannot persist in the form shown for any length of time. The suggestion is that in the case of skin-friction a surface distribution of vortices may be formed as in Fig. B, but which will undergo a transformation by a gradual absorption of the live stream as depicted in Fig. C. These figures are purely diagrammatic, but serve to explain the nature of the system of flow characteristic of the present conception. A point is that the vortices, presuming them to be formed, being bound to the solid surface are not unstable as in the case of the free vortices in Fig. A. He went on to say that this suggestion was put forward for the consideration of those who had facilities to investigate and deal with skin-frictional phenomena. He thought the idea worth serious consideration. Finally, he urged that in the theoretical study and investigation of all such matters the first step should be to endeavour to form some physical conception of what is taking place before attempting to apply mathematical treatment. Some mathematicians were far too ready to rush in with x, y, z, and u, v, w (with and without the prefix d) before giving sufficient attention to the physical attributes of the problem in question, at least this was his experience.

Mr. CLARKSON (The de Havilland Aircraft Co., Ltd.): He was particularly interested in Professor Melvill Jones pitot traverse method of measuring drag. One of the most attractive things about it was the speed with which it appeared to enable firms to conduct accurately, certain types of full-scale test work which might otherwise occupy months of delay in waiting for suitable weather conditions. He instanced, as an example, the fact that his firm had been waiting since the middle of September for suitable weather to measure the drag of certain degrees of roughness as applied to the wings of one of their aircraft; measurements being made by timed speed courses at ground level. It seemed to him that with the pitot traverse method the results could have been obtained more directly, with greater accuracy, and in a fraction of the time, by making measurements at some altitude where atmospheric conditions were steady on numerous occasions when conditions at ground level were unsuitable for speed course measurements.

It was difficult for firms to measure the degree of their surface roughness in order to relate it to Prof. Melvill Jones's limiting roughness criterion given in the paper, and to artificial roughness used by the N.P.L. and others in experiments. It was, presumably, possible to send samples to the N.P.L. for roughness measurement, but it would be valuable if firms had a ready and quick means of measuring the degree of roughness of various fabric, metal, and other surfaces themselves.

Professor Jones had talked of expressing roughness values in terms of diameter, and that implied a spherical shape of particle, but did they know whether there was much difference between spherical and possibly triangular excrescences? Again, he questioned whether the kind of surface produced by roughening with carborundum, for example, was the type of roughness existing on actual aeroplane surfaces.

Mr. W. E. GRAY: He asked Professor Melvill Jones whether the information given in the paper was up to date, the question being prompted by the fact that for years they in this country had been accustomed to receiving information when it was decidedly old. It was notorious that a terribly long time elapsed before the results of researches were published in Reports and Memoranda; he did not know who was responsible.

The PRESIDENT: It is hardly fair to charge Professor Melvill Jones with that.

Mr. GRAY: He admired Professor Melvill Jones's work, but he did want to

know whether the information contained in the paper was up to date; he felt it was time that somebody raised the matter at a meeting of the Society, which body existed to further aeronautical knowledge. It seemed to him that research rather resembled a relay race; if the information were disseminated promptly, other workers could perhaps carry it a step further. Delay in publication seemed to slow down the whole course of research.

The PRESIDENT: If there were some evil spirit which delayed the publication of research reports, it must be taken that he was that evil spirit! It was perhaps not surprising that on occasions there were reports which it was proper that British industry should have a chance to consider before general publication ensued.

Mr. E. F. RELF (*Fellow*, National Physical Laboratory): He had very much enjoyed the author's lucid description of the phenomena of the boundary layer. Although those phenomena were as common as bread and butter to workers in that field, it was a very good thing that they should be written down in simple language from time to time, as had been done in the paper, for the benefit of all and sundry; that helped those who were deeply immersed in the subject as well as those who were not so deeply immersed.

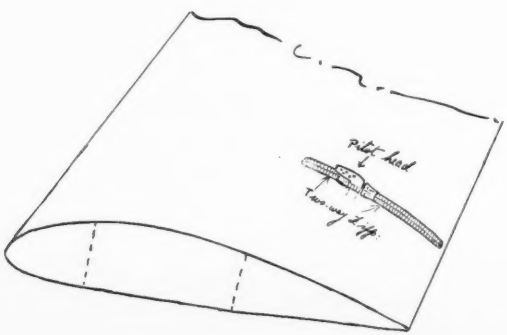
It seemed that Lewis Carroll was responsible for one of the words used in aeronautics. It was quite obvious that the Jabberwock could fly stalled, for it was definitely stated that it "burbled as it came." Mr. Relf believed that that was the origin of the application of the word "burble" to stalling!

In order to emphasise the importance of making measurements of profile drag on many objects, Mr. Relf exhibited a slide indicating calculated values and results of tests on smooth aerofoils of various thicknesses in the compressed air tunnel. But they were still very much in the dark, he added, as to what happened at still higher Reynolds numbers, especially on thick sections, and it was proposed to make experiments in the compressed air tunnel, at Reynolds numbers as high as they could achieve in present-day flight, applying the pitot-traverse method. By applying that method they would very soon learn a great deal more about the drag of wings in flight.

Mr. G. TILGHMAN RICHARDS (*Fellow*): Referring to the point raised by Mr. Clarkson as to a simple method of measuring surface roughness, his attention had recently been drawn to a simple apparatus used by Mr. Harry Shaw, his "Contourograph," which is described in brochures circulated by Acheson's Colloidal Graphite, whereby the surface of even a Gypsy cylinder looks like an outline of the Himalayas.

It would seem that some definition of roughness, such as the curves given by this method, is desirable in order that the results of research of roughness effects in the minute viscous layer could be correlated.

Mr. P. NAZIR (*Associate Fellow*): The problem of locating the point of transition from laminar to turbulent flow on a wing surface, led him to suggest



that instruments fitted to external surface of the wing, as illustrated in Figs. 12, 13 and 14 in the paper, might create such disturbance as would upset very considerably the value of the readings obtained. Therefore, he suggested that the comb or other instrument should be carried *inside* the wing, and that a thin slot should be cut along the upper surface of the wing across the chord, through which slot, only the head of a small pitot tube should protrude. Thus the tube could protrude at any desired position across the wing, and even manipulated while flying. The greater part of the slot could be sealed or closed by means of a doped strip, or special two-way zipp fasteners. He illustrated his proposal by means of a sketch.

Mr. W. S. Farren (*Fellow*): He recalled some recent experiments referred to in a paper by H. Schlichting (Ref. 2 in Professor Melvill Jones' paper) in which an organised form of roughness on flat plates such as one might imagine would be an approximate equivalent of rivet heads on wings, etc., was examined. The results could be expressed, at any rate roughly, by a formula or rule which might perhaps be of some use. Taking for example, the effective roughness produced, as one might imagine it, by arranging trees in an orchard in a regular manner, if the spacing of the "trees" were of the order of five times their height they provided the same resistance as the standard form of "sand-roughness" of the same height. If the spacing were greater, the resistance fell, whereas, if the spacing were closer up to a certain point the resistance rose. When the "trees" were very close it fell again to the standard value. Those results seemed quite natural. In aircraft one was interested in a less regular and on the whole a sparser distribution of roughness. For example, in a typical distribution of rivets the spacing was much greater than five times the height. If the spacing were increased to twenty times the height of the "trees" the effective roughness was reduced to about 1/10th their height. This suggested that rivets might produce a drag which was appreciable. The results seemed to apply remarkably well to spheres, conical rivets and rounded flat rivets. Mr. Farren exhibited a slide from Schlichting's report.

Similar experiments with what one might describe as "hedges"—continuous or interrupted ridges across the plate—gave much higher increases of drag. The work had been done in water, apparently mainly in connection with ship resistance.

Enlarging upon the suggestion by Professor Melvill Jones, that experiments on the lines suggested in the paper might conceivably be done in flight by the aeroplane constructors, Mr. Farren emphasised, from his personal experience, the extraordinary simplicity of the work and the fascination of watching what was happening to the drag of the wing surface whilst in flight. He and his colleagues worked with the instrument, described by Prof. Jones, in which pitot tube could be moved about on and near the wing, an instrument which had some points in its favour, though it was not preferred by everyone.

He was surprised to think that anyone who was concerned with the design of aeroplanes in these days should feel that it was not worth while to find out the magnitude of the drag of what was after all a large and important part of it, with a view to improving his design in future. It could not yet be said that it could be applied anywhere. There were technical difficulties, for instance, in applying it behind ailerons, where there was nowhere to attach the instruments, but these could be overcome. It was important to develop the method so as to be able to make measurements inside the slipstream of the screws. This also could probably be done, and he felt, personally, that if he were an aeroplane designer, he would start using the method without delay.

Mr. F. Radcliffe (*Associate Fellow*): Professor Melvill Jones, having made the aeronautical world accustomed to the term "streamlined aeroplane" some seven years ago, had now introduced the term "aerodynamic smoothness," which also should achieve a similar amount of popularity. The meeting had been led to understand that a certain amount of roughness was permissible; in that connec-

tion, Mr. Radcliffe asked, what was the probable thickness of the moisture film on the leading edge of the wing, referred to by Mr. Serby, which had caused its aerodynamic smoothness to disappear, because one would expect a moisture film to have very little effect indeed? The N.A.C.A. had recently published a collection of results obtained on a family of aerofoils where the maximum ordinate was arranged from very near the leading edge to well beyond .5 of the chord; and Mr. Radcliffe asked whether tests had been carried out in this country, taking into account the published data on those related aerofoils, with a view to finding out how the transition point moved when the point of maximum thickness was moved backwards. The aerofoils illustrated at the meeting were of quite conventional type, but it would be very interesting to make tests with aerofoils that were very much exaggerated in that respect.

With regard to the challenge thrown out by Professor Melvill Jones, that aircraft constructors might carry out full-scale tests, using the pitot tube apparatus, Mr. Radcliffe said he was informed that details of the apparatus could be obtained from the Royal Aircraft Establishment free, gratis and for nothing; therefore, there was no reason why those in the aircraft constructing industry should not carry out some research for themselves.

Mr. W. O. Manning (*Fellow*): Had acoustical methods been applied in the investigation of drag problems, for it appeared to him that turbulence must make a noise? That noise need not be within the ordinary audible range; but it would seem that by traversing a microphone over the surfaces of the plane the occurrence of the transition could be heard and the transition point could be determined in that way, because presumably laminar flow would produce no sound at all, whereas turbulent flow would.

Such a method might also be used in another way. Assuming that on a certain wing section at a certain speed, with the smoothest plane that could be made, the noise level at a certain distance from the leading edge had been definitely measured, then if the plane were rough and thereby caused additional resistance, that additional resistance would be closely proportional to the increased noise at that point due to increased turbulence; in the same way the additional resistance at certain obstructions, such as inspection holes, etc., might also be estimated fairly closely. Apparatus for that sort of work was fairly easily available and measurements could be made without difficulty; it appeared that the method might be useful, particularly as the apparatus could quite easily be housed inside the wing, the microphone being close to the skin.

It would seem also that acoustical methods might be applied to the analysis of the sound produced by the boundary layer. It is clear that the frequencies that would be found would be related to the turbulence pattern and it would seem that information would be available which could hardly be obtained in any other way. Such an analysis of the start and growth of a boundary layer might provide information of great importance.

Mr. M. L. Bramson (*Fellow*): Did the expression "aerodynamic smoothness" include the state of the air? In other words, did the initial degree of turbulence in the air have a considerable effect on the position of the transition point? If so, did it matter whether that turbulence was of substantial magnitude, such as was found due to the rough state of the air near the ground, or whether it was only of almost molecular amplitude such as presumably would be found much higher up? Arising out of that, Mr. Bramson asked whether there was a particular altitude at which the turbulence was so slight that it had not a considerable effect on the total resistance.

Bearing in mind that Professor Melvill Jones had given a standard to work to with respect to the streamlined aeroplane, Mr. Bramson asked whether he could give some corresponding criterion so far as skin friction was concerned; in other words, was there a theoretical limit to the degree to which the transition point might be pushed back on a given surface? And what would be the performance of the ideal streamlined aeroplane, with completely laminar flow?

Finally, Mr. Bramson recalled that the editor of a well known semi-technical paper having a large circulation had recently given vent to the view that skin friction did not matter; it was hoped, he said, that that editor would give equal prominence to the opposite view which had now been clearly established as a fact.

Mr. E. F. RELF (*Fellow*): Replying to Mr. Manning's question concerning the use of a microphone for the purpose of detecting the occurrence of the transition from laminar to turbulent flow, he said that acoustic methods had been tried; by means of a microphone one could detect the change quite definitely, but in most cases in practice there were so many vibrations of different kinds occurring that the use of that method was difficult.

Mr. MANNING: Those other vibrations could be cut out by a properly tuned circuit.

Mr. RELF: That was difficult; if the method could be used under otherwise silent conditions it would be excellent.

Professor MELVILL JONES: He understood that a stethoscope had been used.

Mr. RELF: By means of a stethoscope through holes in the surface one could hear the change, provided other vibrations were reasonably quiet; that was the real difficulty about applying the method to an aeroplane in flight.

The PRESIDENT: He expressed the very great pleasure which it afforded the Air Ministry to support the work of Professor Melvill Jones at Duxford. He expressed his conviction that the money there spent yielded a higher dividend than that on any other Government investment.

Dr. F. W. LANCHESTER, LL.D., F.R.S. (*Hon. Fellow*) (*communicated*): (1) After reading Professor Jones's paper with considerable care he confessed that he did not feel clear as to the distinction (concerning the boundary layer) between what Professor Jones terms the "viscous sub-layer" and the "displacement layer" (or "displacement thickness") which he understood is that marked *black* in Fig. 1. Also in Professor Jones's opinion is the viscous layer representative of the conditions where there is laminar flow, or does it only make its appearance after the point of transition is passed? Actually he had always been a little in doubt as to the use of the term *boundary layer* and had in consequence been careful not to use the expression. The actual adhesion of the fluid (air) to the surface establishing kinetic continuity, in any real fluid has to his knowledge been well known for the last forty-five years, and probably many more, and this adhesive film he took to be the foundation of the *boundary layer*. The question seems to be how to define the outer limit, and if, as he suspected, it cannot be defined, how should the term be applied—(*a*) in the region of laminar flow, (*b*) in the region beyond the transition point where turbulence sets in? In the latter case does the boundary layer totally exclude the region of turbulence or may it include any part of it?

(2) The upper and lower graphs in Fig. 1 to him presented a source of difficulty. Looking upon the aerofoil as a heavy spar section one should certainly find some small degree of augmented drag due to the relatively higher velocity of the air both above and below. In the case of an aerofoil, on the principle of superposition, this would lead one to anticipate a greater increase on the upper graph than decrease on the lower one. This is a rather controversial point, there is some evidence in favour given in the reprint edition of the writer's "James Forrest" lecture of 1914,* Appendix I.

(3) The fact that a region of rising pressure tends to instability and a falling pressure to stability, has long been known in relation to venturi nozzles. It being understood that in accordance with hydrodynamic principles (irrotational motion) the pressure is least where the velocity is greatest, the flow in the entry of the *vena contracta* is comparatively stable, the contraction may, therefore,

* "The Flying Machine from an Engineering Standpoint," Constable & Co., London.

be made very rapid (Fig. A), on the other hand, the flow in the expanding part of the nozzle is in a region of increasing pressure and this pressure difference tends to reverse the direction of flow in the region of the wall where the fluid is stagnant, and so tends to initiate turbulence. The law so exemplified is, he believed, universal.

FIG. A.

(4) He thought that a correction was needed to Fig. 6. There is conflict between the scale on the left of the figure and the note beneath. The latter appears to be correct when it says:—" Referred to the left-hand scale the curves represent approximately the drag incurred between the leading edge and any given point on the surface." The inscription (lb./sq. in.) at the head of the scale is incorrect,* also the decimal points should be deleted. He had checked the graph at two points in this connection thus:—

At 10ft. from leading edge.—Reynolds number at 290ft. sec. $= 290 \times 10/0.000154$ $= 1.9 \times 10^7$ corresponding value of C_f ($= C_o$ in his recent paper)†

$= 0.0013$ pounds/sq. ft. $= (0.0013 \times 0.078 \times 290^2)/32.2 = 0.265$.

This on one foot width $\times$ 10ft.; drag $= 2.65$ pounds.

At 2ft. from leading edge.—Reynolds number $= 3.8 \times 10^6$, $C_o = 0.0014$, and pounds per sq. ft. on same basis $= 0.285$. This on strip area 2 sq. ft. $= 0.57$ pounds. These agree quite closely with the graph given for a smooth surface.

A similar agreement exists between the curve for smooth surface given in Fig. 7; compare Fig. B. It is to be remarked that all distances after the first foot (at which $N_R = 1.9 \times 10^6$) are to be regarded as high Reynolds numbers. The conditions within the first foot from the leading edge may be regarded as approximately covering the range of low Reynolds numbers including the condition of instability, where the value of C_o is in doubt.

In the paper it is mentioned that the transition with a smooth surface has been brought back to a point 20in. from the leading edge in one particular case. He found the Reynolds number $= 3 \times 10^6$ which is only just clear of the unstable region defining the lower limit of the Reynolds number. This is not without interest.

(5) He confessed himself a little sceptical on the subject of the theory of roughness as set forth. They seemed to be faced with two different Reynolds numbers working in double harness, one relating to the fore-and-aft length of the surface, and the other relating to the thickness of the " viscous layer." He had more than once expressed the opinion that the simultaneous use of two different physical bases, giving two expressions for the Reynolds number, is fundamentally wrong. *Either* the law of similarity is thereby infringed, *or* the two values are in constant relation to one another in which case the second parameter is redundant. There may be some special reason by which the treatment may be justified: a word or two of explanation would be welcome.

(6) Finally, he would like to ask Professor Jones to give his reason for adopting a *chisel edge* at the point of entry of the planes as shown in Figs. 2, 5, 6, and 7; this feature is new to the writer.

* If this were the meaning the curves would rise towards the left of the diagram and not fall. The description at the head of the scale should read, " Drag in pounds *per foot width* between leading edge and point indicated."

† " The Part played by Skin-friction in Aeronautics," Fig. 2.

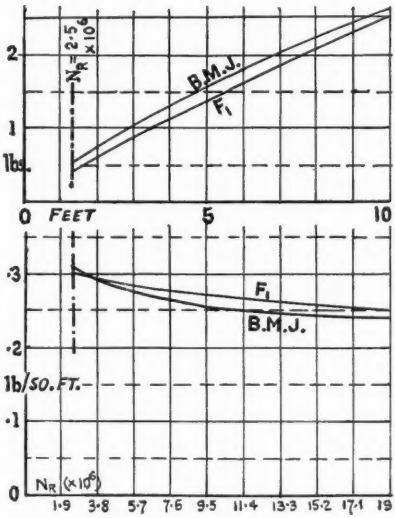


FIG. B.

The calculation on which the graphs F_1 F_1 are based is as follows:—*

lbs./sq. ft. $= C_0 \times (\rho V^2/32.2) = C_0 \times 202$

$V = 290$ ft./sec.

1	2		3		4
L (feet)	C_0	×	202	×	L
2	.00145		.294		.585
4	.00138		.279		1.116
6	.00133		.269		1.614
8	.00128		.259		2.072
10	.00124		.250		2.500

* C_0 in each case is derived from Fig. 2 in paper of November 12th.

The upper diagram in Fig. B is a comparison between Fig. 6 of the paper (smooth surface) graph marked B.M.J., and the results given by the late William Froude for tinfoil surface. The lower diagram similarly refers to Fig. 7 of the paper. The actual diagrams in Prof. Jones's paper are drawn to a smaller scale, and as redrawn they are not quite consistent; thus, in the upper figure which represents the total drag on one foot breadth of surface shows for the whole ten-foot width 2.6 pounds, whereas in the lower graph, giving the mean per square foot for that width (10ft.), the reading as plotted is .24 which, multiplied ten, gives 2.4 instead of 2.6. If the two are averaged the mean falls exactly on the graph F_1 and it does so for all values greater than 4ft. from the "cut-water." For values less than this the mean B.M.J. graph shows a somewhat higher drag than that given by Froude. The curves are not extended below the value of $N_R = 2.5 \times 10^6$, this being generally agreed as the limit below which instability gives rise to doubt. It would be of interest if Prof. Jones would state the source of his data given in these figures, the agreement with Froude's determination of same three-quarters of a century ago is remarkable.

The apparent discrepancy between the B.M.J. graph in the upper and lower figure may possibly have been introduced in the replotting of Prof. Jones's figures.

REPLY TO THE DISCUSSION.

The President, in opening the discussion, has laid his finger on what I regard as the most important conclusion to be drawn from my paper, that the method of measuring drag by means of an exploring pitot is peculiarly suitable for use by the firms. If the lecture does nothing else but succeed in convincing designers that there is a method by which they can carry out drag experiments for themselves without great expense it will have achieved its main object. Referring to the President's remarks about the use of wool-tufts, I would like to mention

here that this method was not initiated by me but was suggested and evolved by Mr. J. A. G. Haslam.

I am inclined to agree with Mr. Serby's view that the fixed comb of pitots is more convenient for general use than the moving pitot behind the trailing edge, which we use for measuring drag at Cambridge. For various reasons the moving pitot suits us for research work, but I do not think that for routine purposes it would be so convenient as the comb. I agree also with Mr. Serby's view that we now want to know how much the drag is increased by the ridges made by inspection panels, etc.; we have some experiments on this matter in hand at Cambridge. The experiment at R.A.E. to which he refers, in which drag was increased 20 per cent. by moisture deposited on the wings in flight, is of great interest; one wonders whether this was brought about by a forward movement of the transition point or merely by the effect of increased roughness on the drag of the turbulent boundary layer.

Dr. Lanchester's question whether a laminar boundary layer would result in an earlier stall, as it does on a sphere, is very much to the point. It appears from our experiments that, as wing incidence increases, the transition point on the upper surface moves forward towards the leading edge and it may be that before the stall occurs it has moved sufficiently far forward for the boundary layer to be turbulent in the critical region. However this may be, I know of no experimental evidence showing that a smooth upper surface leads to an earlier stall. Dr. Lanchester also enquired why it was that I began by dismissing induced drag as being of minor importance in our present discussion, when it can easily be shown that, if profile drag coefficient were constant, minimum total drag would occur when induced drag and profile drag are equal. There are two reasons why we do not at present realise the ideal condition of minimum drag to which Dr. Lanchester refers when flying at top or cruising speed. The first is that the area of our wings is much larger than would be ideal for high speed flight, on account of course of the necessity of landing and taking off. The second is that Dr. Lanchester's ideal minimum generally occurs at so large an incidence that profile drag has begun to rise rapidly by partial stalling. For these reasons high speed flight occurs at present at incidences well below the ideal; it may be that when we take to flying at great heights this will not be so, and induced drag may rise to equal importance with profile drag in the determination of top and cruising speed. Dr. Lanchester's conception of the form of the vortices in the boundary layer near a solid surface are very interesting and should provide thought for the more mathematically minded amongst us. Dr. Lanchester asked whether the drag caused by the laminar layer is now taken as proportional to the 1.5th power of the speed. The answer is in the affirmative.

I am glad that Mr. Clarkson agrees with me that the method of the exploring pitot is suitable for use in his firm. With regard to the direct measurement of the degree of roughness of a surface, an answer respecting the possibility of making such measurements is given later in the discussion by Mr. Tilghman Richards and some remarks bearing upon the effects of roughnesses of different kinds are made later by Mr. Farren. My present view is that roughness may take so many different forms that it will probably be safer to measure the effects of each kind of surface finish directly, by using the exploring pitot in flight or in other ways, rather than by trying to measure the roughness and then estimating the resistance it will produce. The formula which I gave for the limiting size of roughness of the type which occurred in Prandtl's experiments was given more as a guide to the order of magnitude of the roughness than as a universal figure which would apply to the roughness of any form.

In answer to Mr. Gray, all I can say is that the lecture is naturally as up to date as I can make it. It may well be that there is more information available of which I am unaware, but I am obviously not the right person to ask about that.

I am obliged to Mr. Relf for showing a slide containing results obtained at N.P.L. for thick and thin wings. These results are of interest in showing what has actually been found in the wind tunnels, but I avoided dealing with such results in my paper because I do not know yet how they are to be interpreted in relation to free flight with high values of the Reynolds number.

Mr. Tilghman Richards' description of an apparatus for measuring surface roughness is of great interest. I am obliged to him for drawing our attention to it.

In answer to Mr. Nazir, it is, of course, always possible that the brackets carrying the exploring pitot may set up pressure gradients which might influence transition of the boundary layer from the laminar and turbulent form, and that this could, to some extent, be avoided by burying most of the supporting structure within the wing. But in order to carry out work quickly upon a variety of wings and surfaces it is more convenient to attach the whole apparatus outside the wing and it is then, of course, necessary to make some experimental or theoretical estimate of the pressure gradients set up by it. This, however, it is not difficult to do when all that is required is the order of magnitude of the added pressure gradient. We feel fairly confident that in the experiments we have made no serious errors were introduced from this cause.

I am obliged to Mr. Farren for his clear summary of Schlichting's work on various kinds of roughness. This work should enable the effects of certain different kinds of roughness to be compared with what might be called Prandtl's standard roughness, which consists of small approximately spherical particles adhering to the surface very close to one another. With regard to the second part of his contribution to the discussion, I have already indicated my agreement with the view which he so forcibly expressed, that firms should make their own experiments on the problem of drag reduction.

In answer to Mr. Radcliffe, the idea that a surface could be aerodynamically smooth when it is not in fact absolutely smooth was not, as Mr. Radcliffe seems to imply, originated by me; it has been well established for some time. We have not yet made many experiments upon wings of various section as he suggests should be done; full-scale work of this kind is necessarily slow unless an enormous amount of money is expended upon it.

In answer to Mr. Bramson, aerodynamic smoothness as I have used the term applies only to the effects of roughness upon a turbulent boundary layer and not to the effect of roughness on the transition point. So far as I know, moderate turbulence in the outer air does not affect the turbulent boundary layer appreciably. Transition from the laminar to the turbulent form is, however, effected both by surface roughness and by external turbulence in a manner about which we as yet know very little. I have explained in the paper that I know of no theoretical limit to the extent of the laminar boundary layer, but that in spite of this it seems improbable that we shall be able to make it extend much beyond the first one-third of the wings, and that even this is problematical with very high values of the Reynolds number. In answer to his question as to what would be the gain if the boundary layer were laminar over the whole surface of the aeroplane, Figs. 6 and 7 in the paper show that for a flat plate the drag would be reduced about eight times, but whether this would occur upon the curved surfaces of an aeroplane is problematical because, as Dr. Lanchester pointed out, separation of the flow from the surface occurs more easily with a laminar than with a turbulent layer, so that in the unlikely event of a completely laminar layer occurring over the whole surface, it might well be that form drag would be increased and that therefore the full advantage suggested in Figs. 6 and 7 would not be realised.

In answer to Mr. Lanchester's written communication the term viscous sub-layer (or laminar sub-layer as it is sometimes called) applies to the very thin layer of fluid, lying between the solid surface and the turbulent part of the turbulent boundary layer, in which the motion is approximately laminar and the

mean velocity is roughly proportional to the distance from the solid surface. I called this the viscous sub-layer, avoiding the more usual term laminar sub-layer, because I am not sure that the motion within it is strictly laminar, whereas it certainly is greatly influenced by viscosity. The term has no application to the strictly laminar part of the layer in front of the transition point.

As Mr. Lanchester suspects, the thickness of the boundary layer cannot be exactly defined because the mean velocity within it approaches asymptotically to the value in the undisturbed stream; sometimes the thickness is defined by the point where the velocity has reached some specified fraction of the final value, and at other times it is defined by reference to some integration across the layer. Thus the displacement thickness used in Fig. 1 may be defined as:—

$$\int_0^\infty \{ (U-u)/U \}\, dy$$

where U is the velocity in the external stream and u is the mean velocity at distance y from the solid surface. Again, a quantity, sometimes called the momentum thickness, is defined as:—

$$\int_0^\infty \{ u\,(U-u)/U^2 \}\, dy.$$

Referring to Mr. Lanchester's question 4, the quantities plotted in Fig. 6, when related to the left-hand scale, represent the drag per unit span of wing divided by the wing chord. Thus, in this figure, the value at the end of the curve, 10ft. from the leading edge, shows the mean drag per square foot of wing at that section, whilst the smaller values taken from the curves at points nearer to the leading edge, show what parts of this drag have been incurred between the leading edge and those points.

A Reynolds number based on boundary layer thickness is nowadays used for certain purposes in all fluid dynamic laboratories. The tacit assumption is that phenomena under consideration depend only on the thickness of the layer and the velocity gradient in the direction of flow outside it, and not upon what is happening far upstream or downstream of the part under consideration. The chisel edge in some of my figures occurs merely because I wanted to convey the idea that the abscissæ of the diagram represent distance along a plate from its leading edge. It is not intended to imply that the actual plate would have this shape.

The 614th Lecture read before the Royal Aeronautical Society since its foundation, January 12th, 1866.

PROCEEDINGS.

A meeting of the Royal Aeronautical Society was held in the Lecture Theatre of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2, on Thursday, January 14th, 1937, when a paper on "Magnesium Alloys" was read by C. H. Desch, Esq., F.R.S.

In the chair: Major J. S. Buchanan, F.R.Ae.S., Member of Council.

Major J. S. BUCHANAN: The Society had always been fortunate in being able to persuade men of distinction to spare time to talk to it on their special subjects, and it was his pleasant duty to introduce another distinguished lecturer that evening in the person of Dr. Desch, who would speak on the latest research work on magnesium alloys. Dr. Desch needed very little introduction. He was Superintendent of the Metallurgical Department of the National Physical Laboratory. Before taking that appointment he was Professor of Metallurgy at Sheffield University. He was also a Doctor of Science of London University, a Doctor of Philosophy of Würzburg, and a Fellow of the Royal Society. The subject with which he was going to deal was of the greatest interest to all concerned in aeronautical engineering and one about which Dr. Desch was peculiarly fitted to speak.

Dr. C. H. DESCH then read his paper entitled "Magnesium Alloys."

MAGNESIUM ALLOYS.

By C. H. DESCH, F.R.S. (National Physical Laboratory).

SUMMARY.

An account is given of developments during the last three years in the production of light magnesium alloys suitable for aircraft construction. The heat-treatment of castings and the hardening by ageing of forged alloys are considered as well as the conditions affecting forging at various temperatures. The connection between these properties and the crystalline structure of magnesium is discussed.

Three years ago Dr. Aitchison read a paper before this Society on "Light Alloys for Aeronautical Purposes, with Special Reference to Magnesium" (1). He then described the many uses in aircraft of alloys composed mainly of magnesium, as well as those of certain alloys of aluminium containing magnesium as their principal alloying element. Since that date, the interest of aircraft constructors in magnesium has greatly increased. As the standards of aircraft performance are raised, possible saving of weight becomes of ever-increasing importance, and attention is naturally turned to those metals which are of low specific gravity.

When the original arrangements were made for this paper to be given, it appeared likely that by the time that it was presented certain new alloys of magnesium would have been sufficiently tested, and that an account of their performance in service could be given. This hope has not been entirely fulfilled. The development of new materials is apt to take longer than is expected, and in this instance it is only possible to describe in general outline some new directions in which progress is being made.

Since the light metals of the alkalies and alkaline earths are ruled out by their chemical activity as well as by their softness, only beryllium and magnesium are

left among the elements lighter than aluminium. Beryllium has unfortunately disappointed expectations, for although its crystal structure indicates that it should be possible to render it ductile, all the metal so far produced has proved to be brittle, nor has any means been found of alloying it with small quantities of another metal so as to make it ductile. With a specific gravity of only 1.84, an elastic modulus which is stated to be very high, and a melting point of 1,278°C., beryllium would seem to offer remarkable advantages, but the long investigations carried out in Berlin and at the National Physical Laboratory have not resulted in the production of new light allows, although attention is now being again directed to the alloys with aluminium (2). At the other end of the series, alloys of copper and of nickel, containing small quantities of beryllium, have shown remarkable properties and have found technical application. The metal still continues to attract inventors and prospectors, from the feeling that it would be an admirable material of construction, alone or in an alloyed form, if only it could be produced in a suitable condition.

It might perhaps have been expected that a useful alloy could be made by combining beryllium with magnesium. Both metals belong to the same group in the periodic system. Both are light metals, and both crystallise in the same system (close-packed hexagonal). Yet experiments at the N.P.L. showed, not only that the two metals do not form a homogeneous alloy in the solid state, but that molten magnesium does not even dissolve beryllium (3). This appears to be due to the very different sizes of the atoms. The magnesium atom is much larger than that of beryllium, the effective atomic diameter being 3.20Å. against 2.25Å. for beryllium, and spheres of such different sizes will not pack closely together. It is remarkable how often purely geometrical factors outweigh those of chemical similarity in determining the structure of alloys, and new light is constantly being thrown on metallurgical problems by the application of ideas of atomic arrangement in metallic crystals. It is becoming more and more possible to decide beforehand which elements may with advantage be added to a given metal to produce a useful alloy with given properties, although the complexity of most of the mechanical properties prevents the process from being quite simple. It may, however, be said that theoretical knowledge plays an ever-increasing part in the development of alloys.

The production of magnesium has increased in recent years, although figures are difficult to obtain. The most convenient source is still the mineral carnallite, a double chloride of magnesium and potassium, from which the metal is obtained by a fairly simple process of electrolysis, but as this mineral is of quite local occurrence, apart from the extensive deposits of Strassfurt and elsewhere in Germany, other countries have made efforts to use more available sources. These include sea water, which contains the chloride; the native carbonate, magnesite (the most widely used); and dolomite, the double carbonate of magnesium and calcium, which demands a preliminary separation of the compounds of the two metals from one another. Several processes are therefore in use, and these are no longer confined to electrolysis, as a purely thermal reduction at a high temperature, although involving great difficulties in the construction of plant, has been successfully used on a manufacturing scale (4, 5), and has lately become a serious rival to the older process.

Magnesium is too weak a metal to be used in the unalloyed state, and the metals which may be added to it to produce strong alloys are very limited in number. This may be deduced on theoretical grounds. Hume-Rothery has shown that solid solutions, which are necessary for any considerable strengthening, cannot be formed to any appreciable extent if the atomic diameter of the added metal differs from that of the solvent metal by more than about 14 per cent. (6). When this rule is applied to magnesium, it is found that the following metals fall within the limits:—Lithium, aluminium, zirconium, silver, cadmium, tin, antimony, gold, mercury, thallium, lead, and bismuth. Several of these, however, including tin, antimony, thallium, lead, and bismuth, form compounds with magnesium

which are both brittle and reactive, so that they can only be added sparingly, if at all, and when all the factors are taken into account, we are left with only aluminium and cadmium as suitable for alloying in more than quite small quantities. On the other hand, calcium, cerium, zinc, nickel, cobalt and manganese, which fall outside the limits, and can only form solid solutions to a very limited extent, have proved useful in small quantities. The conditions in ternary systems have been less completely determined, but they are now being studied systematically at the N.P.L. (7).

To those who have only known magnesium in the form of ribbon or powder for use in flashlights, and have noticed its ready inflammability, it is rather surprising to find that magnesium alloys are remarkably easy to cast. This comes partly from the fact that molten magnesium has very little power of dissolving gases, such as hydrogen, so that ingots and castings do not suffer from the sponginess caused by the liberation of dissolved gases at the moment of freezing. At the last International Foundry Exhibition in Düsseldorf, large ingots of magnesium alloys were shown, sectioned down the middle, and the absence of cavities beyond the first 2 cm. from the top was striking. This soundness is naturally of great advantage in the making of castings. The shrinkage of magnesium alloys in the mould is nearly the same as that of the common casting alloys of aluminium (8). It is, of course, necessary to use a suitable flux, consisting of mixtures of chlorides and fluorides, to protect the surface against oxidation, and to use a protective atmosphere during pouring, but these conditions are now well understood, and no difficulties are experienced in the foundry. The protective atmosphere is obtained by mixing certain substances, notably sulphur, boric acid, ammonium bifluoride, or mixtures of these, with the sand used in moulding, and sprinkling the same compounds on the surface of the metal during pouring. During annealing processes, a similar protection may be obtained in one of two ways, both of which are in industrial use (9). Either a muffle may be used, in which an atmosphere rich in sulphur dioxide is obtained, as for instance by strewing the floor with iron pyrites, or the objects may be heated in a salt bath, a suitable composition being 72 per cent. sodium dichromate, 24 per cent. potassium dichromate, and 3 per cent. potassium chromate, the last-mentioned salt being added to prevent the gradual reduction by magnesium which would otherwise form a sludge. Mixtures of alkali nitrates and fluorides are also used. Simple nitrate baths, as used for aluminium, are out of the question on account of chemical attack. These precautions show that a special technique has to be adopted in the making of castings or forgings of magnesium alloys, but that no special difficulties are involved, and a magnesium alloy foundry is in fact a remarkably clean and inoffensive place. Comparatively large gates and risers are necessary, but as the scrap may be remelted with very little loss or deterioration this is not of serious consequence.

Casting Alloys.

Full advantage may be taken of the excellent casting qualities of magnesium for the construction of aircraft parts which are not to be too highly stressed, it being possible to make intricate shapes without great difficulty. The strength may be increased, and the ductility improved, by an annealing treatment which brings a larger quantity of the alloying elements into solid solution, producing a homogeneous structure. A subsequent treatment at a lower temperature, whilst often lessening the ductility, increases the hardness by precipitating a constituent in a fine state. Both sand and chill castings are used. By casting in dies, very satisfactory castings, needing a minimum of machining, are obtained, with a higher strength than sand castings.

One of the most valuable means of increasing the strength of an alloy is by the process known as age-hardening. It is to the results of this process that duralumin and Y-alloy, for instance, owe their advantages over other aluminium alloys which do not undergo special heat treatment. Put briefly, the process

depends on finding some constituent which may be added to an alloy, capable of passing into solid solution at a high temperature and being retained on quenching, but separating, at first in an ultra-microscopic form, when the quenched alloy is heated to a lower temperature, or in some instances even spontaneously at the temperature of the air. Generally speaking, to obtain any considerable increase of strength, the added constituent must have a high solubility just below the melting point, falling rapidly with falling temperature. It is therefore natural to search among the equilibrium diagrams of the binary alloys of a given metal in order to discover systems of this type. Magnesium does not as a rule form extended solid solutions with other elements, but such a search discloses that the following metals, in descending order, have a fairly high solubility when hot, in all cases diminishing rapidly on cooling:—thallium, lead, tin, bismuth, silver, aluminium, zinc, manganese, calcium. Some of these alloys have been only imperfectly investigated, but the order is approximately correct. Several of the metals mentioned, such as lead, can be at once ruled out, both on account of weight and because they form compounds with magnesium which are decomposed by water. One of the chief difficulties with which the metallurgist has to contend in devising new alloys of magnesium is its strong tendency to form compounds, often of a reactive kind, with other metals. The

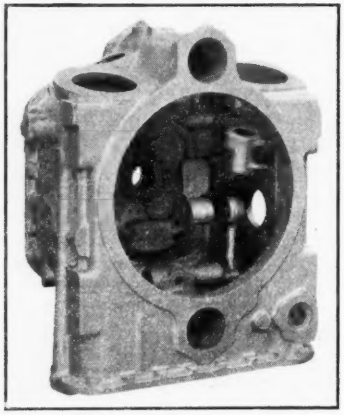


FIG. 1.

Gear casing. Sand casting.

(Messrs. High Duty Alloys)

solution treatment alone improves both the tensile strength and the elongation, but has little effect on the proof stress. The precipitation treatment improves both the tensile strength and the proof stress.

Cast alloys of magnesium with most metals give poor mechanical properties, and only those containing an appreciable quantity of aluminium are strong. In laboratory experiments, the alloys with zinc alone, cast in the form of bars 7in. by 1in., 12 bars being bottom-fed from a central runner, gave a maximum tensile strength of 10.5 tons in.^{2} at 4 per cent. of zinc, but after heat treatment, consisting in heating for 48 hours at 300-325°C., followed by hardening at 160°C. for one or more days, the maximum was moved to 6 per cent. of zinc, the strength being increased to 12.5 tons/in.^{2} (10). The following table gives figures for some casting alloys (11).

Most of the castings of magnesium alloys made in metal moulds are cast by gravity, but true pressure die-casting is also employed with success, certain

precautions having to be taken on account of the reactive nature of the metal, which combines not only with oxygen but also with nitrogen with avidity. Unlike aluminium, the molten alloys do not attack the iron or steel dies. The surface of the metal is protected by an atmosphere of sulphur dioxide and sulphur vapour. The compressed air type of machine is used, with a relatively high pressure (about 50 kg./cm.^{2}) (12).

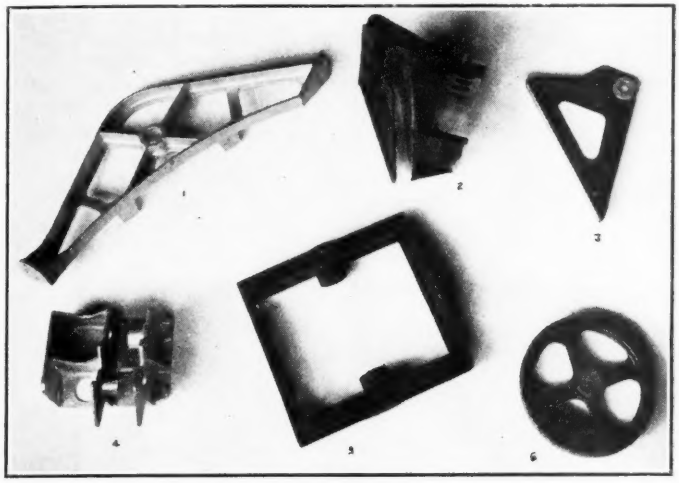


FIG. 2.

"Electron" castings used on Empire flying boats.
(Messrs. Short Bros.) (Details attached)

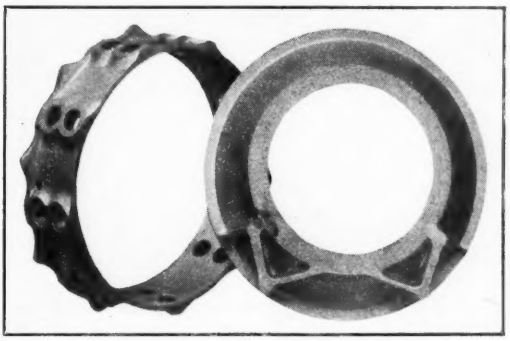


FIG. 3.

Locating ring. Cast in dies.
(Messrs. High Duty Alloys)

Castings of magnesium, like those of other metals, may be examined for soundness by means of X-rays, and the low density allows of great penetration. The exposure for a magnesium casting 6in. thick is the same as for one 4in. thick

CAST AND HEAT-TREATED ALLOYS.

Composition. Al	Mn	Zn	Condition.	Tensile Strength. Tons/in.²	0.2 % Proof Stress. Tons/in.²	Elongation %	Compressive Strength. Tons/in.²	Brinell Hardness.	Izod Impact. Ft. lb.	Fatigue Limit. Tons/in.²
8.0	0.2	—	As cast	10.7 — 12.5	4.5 — 5.8	3 — 7	19.7 — 21.5	47 — 51	2—4	2.7 — 3.4
			H.T.1	14.3 — 16	4.5 — 5.8	8 —12	19.7 — 21.5	47 — 60	5—7	2.7 — 3.4
10.0	0.1	—	As cast	9.4 — 10.7	5.3 — 6.7	1 — 3	21 — 22.5	52 — 57	1—3	3.4 — 4.5
			H.T.1	13.4 — 15.5	4.9 — 6.3	6 — 9	21.5 — 23.3	49 — 55	3—6	4.0 — 4.9
			H.T.3	13.8 — 16	7.6 — 9.4	1 — 4	23.3 — 25.4	65 — 75	1—3	3.4 — 4.5
12.0	0.1	—	As cast	8.5 — 10.3	6.7 — 7.6	0 — 1	20 — 21.9	57 — 61	0.5—2	—
			H.T.3	12.0 — 13.4	8.9 —10.7	0 — 1	23.3 — 25.4	72 — 85	0.5—2	—
6.0	0.2	3.0	As cast	11.2 — 13.4	4.9 — 5.8	4 — 8	—	47 — 51	2—5	4.0 — 4.9
			H.T.1a	14.7 — 16.9	4.9 — 6.3	9 —13	—	50 — 53	4—6	4.0 — 4.9
			H.T.3a	16.5 — 18.7	8.0 — 9.3	3 — 7	—	65 — 72	1—3	4.0 — 4.9

H.T.1 represents a solution heat treatment, consisting in heating 16 hrs. at 420°.

H.T.1a—similar treatment at a rather lower temperature.

H.T.3 and H.T.3a—solution heat treatment as above, followed by heating 16 hrs. at 175°.

in aluminium, but the contrast is weaker (13). It is therefore advisable to use a lower voltage on the X-ray tube than usual. A method has been devised by Messrs. High Duty Alloys for impregnating the castings under pressure with a substance highly opaque to X-rays, thus making the defects clearly visible, but in an exaggerated form. Examples of castings are shown in Figs. 1, 2 and 3.

WORKING PROPERTIES.

The mechanical properties of magnesium, which are shared by its light alloys, and determine their behaviour in rolling and forging as well as their strength and ductility in use, depend on the crystal structure of the metal. Magnesium is one of the hexagonal metals, similar in structure to zinc, cadmium and solid mercury, but having certain peculiarities of its own. In a cubic metal, such as copper or aluminium, there are many similar planes on which slip can occur, so that extensive deformation is possible by alternate slipping on several, but in a hexagonal metal slip only occurs, at least at the lower temperatures, on a single set of planes, the basal planes of the hexagonal prism. Slip in each crystal therefore takes place only in one direction, and deformation is restricted. The process is often complicated by twinning.

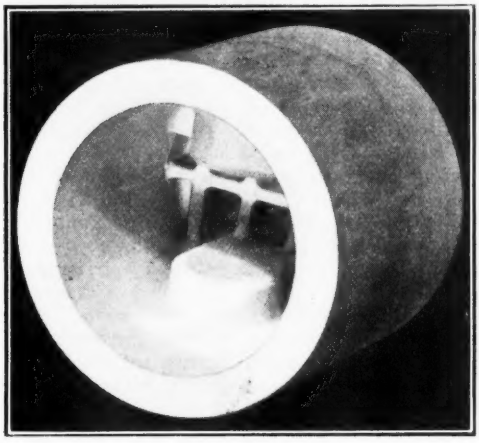


FIG. 4.

Small piston pressing.

(Messrs. High Duty Alloys)

This peculiarity is shared by zinc and cadmium, but the three metals differ considerably in their behaviour on deformation. This is because the hexagonal structures are not quite the same. The unit of structure of each is a hexagonal prism, but that of zinc may be regarded as being slightly elongated, as compared with the most closely packed arrangement possible, whilst that of magnesium is slightly compressed. Although the mechanics of the process are not completely worked out, it is certain that the effect is to make magnesium still less isotropic than the other related metals (14).

It is the presence of these planes of easy slip that makes the deformation of magnesium* so anomalous. In the process of working, the crystals of which the mass of metal is made up tend to rearrange themselves so that their basal

* What is said of magnesium in this section applies also to its light alloys.

planes are as nearly parallel as possible, making deformation in any but one direction very difficult. Thus the yield point in tension differs from that in compression in a forging made under normal conditions. It is even possible to have ductility in one direction and brittleness in another. This difficulty is overcome by making the crystal grains as small as possible. The condition of the ingot largely determines the behaviour of the metal in forging, and small grain size in the ingot is obtained by casting from a high temperature. In the subsequent working the object is to check this "preferred orientation," and this may be controlled by taking advantage of three factors. In the first place, when the temperature of deformation is above 225°C., although most of the slip occurs on the basal plane as before, certain other planes (the "first pyramid" planes) come into play, so that each crystal has six new possibilities of slip. Thus when all the malleability due to the basal plane is exhausted, other planes become available. The second device is that of changing the direction of working. If the metal can be squeezed, first in one direction and then in another, a much greater degree of deformation is possible than in a simple operation, such as rolling. Lastly, the time factor has a very great influence. Magnesium and its alloys may be deformed slowly, when quick working at the same temperature and with the same stresses would cause cracking. The practical working of the alloys takes advantage of all these factors. The ordinary way of breaking down the structure of the ingot, by rolling or hammering, readily causes cracking of magnesium alloys, even when the reduction at each stage is small, and this is one of the principal difficulties of manufacture. On the other hand, when the surfaces of the mass of metal are confined, much greater deformation is possible. Two methods fulfil this condition: extrusion and pressing between heated dies, and both are applied successfully in practice. All the light alloys of magnesium may be extruded, the speed being kept low, and this is the usual method of production of much of the material as used in industry. Besides this, pressing in such a way as to constrain the flow of the metal is very widely applicable. In the experiments which have been made in the course of the study of magnesium alloys at the N.P.L., a 120 ton hydraulic press has been used, having steel dies heated to the required temperature by gas, with a trumpet profile by means of which the original cast cylindrical ingot is reduced in diameter. Several pairs of dies may be used to bring about the required reduction. This method of pressing is of course also applicable to shapes other than the cylinder, and is in fact used for the production of airscrews and of many forgings used in aircraft. The operation calls for the use of very powerful hydraulic forging presses, such as are used in the steel industry. It has been pointed out (15) that pressing at a high temperature gives strong directional properties, as recrystallisation occurs between successive stages, providing new basal planes with a perpetual tendency to become parallel with one another throughout the mass. This tendency is less, the lower the temperature of forging. When a series of operations is necessary, each successive pressing should be at a lower temperature than the last. Drop-stamping and forging are, however, quite practicable, provided that means are taken to ensure a fine grain structure in the initial material. Naturally, care must be taken to work within a suitable range of temperature, and to adjust the amount of deformation at each successive stage by trial.

Rolling gives a structure with highly directional properties. Rolling at a very slow speed allows of much more change of section without cracking than does the practice usual with other metals, and mills run at a very low speed are used industrially. At the N.P.L. an experimental mill has been installed, having rolls 14in. long and 8in. diameter, with gearing allowing the speed to be reduced to 2.5ft./min., and with a range of variation up to 15ft./min. The rolls are uniformly heated by electrical resistance mats placed in contact with them, and giving a temperature of 200° C. conveniently.

The production of sheet naturally presents special difficulties. In rolling, the basal planes of the crystals tend to set themselves parallel with the surfaces of

the sheet, giving a high yield point but low ductility. If, therefore, the sheet has to be bent at all severely in the course of construction, the operation must be carried out hot (at 275°-325°C.). In order to break up the structure as far as possible, Schmidt (15) recommends that the last pass should be a reduction of 10 per cent. by cold-rolling, followed by annealing. Where intermediate annealings are necessary, there is always the danger of excessive grain growth. A certain critical deformation is usually necessary to cause the growth of very large grains when a metal is subsequently annealed, but with magnesium this tendency is strongly marked, and the critical deformation extends over a comparatively wide range.

By repeatedly changing the direction of stress, as mentioned before, the crystal structure can be broken down, largely as the result of repeated twinning, and as the directional properties are lessened, so the ductility is improved. One way of doing this is by passing sheet between staggered rolls, and Schmidt reports a remarkable instance of the very great effect of such treatment. A sheet of the alloy AM 503 (DTD 118) 2 metres long and 2 mm. thick, passed 100 times through staggered rolls, *shortened* by 50-60 mm. The ductility was increased, in some tests being doubled in the transverse, and multiplied five times in the longitudinal direction. Similarly, a cylindrical rod, passed between oblique rolls, increased in diameter and shortened correspondingly.

Wrought Alloys.

It is naturally in the field of wrought alloys that there is the largest scope for the production of new alloys with improved mechanical properties. Magnesium has one disadvantage which cannot be removed by alloying, namely, a low elastic modulus of 6.2×10^6 lb./in.^{2}, against 10×10^6 for aluminium, and this fact must be allowed for in design. On the other hand, the high elastic hysteresis gives it great damping capacity, so that vibrations, as in an airscrew, are prevented from reaching a dangerous amplitude. The alloys are sensitive to concentrations of stress, especially under alternating stresses, so that it is important to avoid sudden changes of section.

The simple binary alloys with metals other than aluminium do not, so far, offer great advantages. Cadmium alloys readily with magnesium, the tensile strength being little changed, even by large additions, but the alloys are very ductile, the elongation increasing with increasing cadmium up to 20 per cent. on 2in. with 15 per cent. Cd, and this property is retained in the ternary alloys with cadmium and zinc. Rolled strip containing cadmium 4, zinc 4 per cent., gave a tensile strength of 17.2 tons/in.^{2} and an elongation of 22 per cent. This strip could be spun cold into simple forms if given several intermediate annealings. Higher strengths, with somewhat less ductility, were obtained from alloys containing cadmium together with aluminium.

For highly stressed parts it is necessary to raise the proof stress as well as the tensile strength, and for this purpose some form of age-hardening would seem to be desirable. Of the metals which might be added to the standard alloys with this object, silver seemed the most promising, and its effect on several alloys has been examined.* It may be mentioned in passing that the fact that the added metal is relatively costly is of little importance. In the production of many objects, the cost of manufacture is so much greater than that of the material that an addition to the cost of the alloy is hardly appreciable in the final product. An alloy with aluminium 8, cadmium 8, and silver 2 per cent., in the form of 1in. forged bars, after a treatment consisting of heating two hours at 410°C., quenching, and ageing for six days at 130°C., gave a tensile strength of 27.6 tons/in.^{2}, 0.1 per cent. proof stress 19.5 tons/in.^{2},

* Patent Application No. 12659. 5/5/36.

and elongation 4.2 per cent. Other alloys, after very similar treatment, gave the following results:—

Composition.					Tensile Strength.	Proof Stress.	Elongation
Aluminium.	Silver.	Zinc.	Manganese.	Calcium.	Tons/in.^{2}	Tons/in.^{2}	%
8.0	2.5	—	0.4	0.2	25.2	17.0	3.5
7.5	2.7	0.7	0.4	0.3	25.8	17.3	6.0
8.5	3.0	—	0.3	0.2	25.1	16.4	4.0

It has been found possible to obtain similar properties, including the high proof stress, from large forgings made in the press. It seems, therefore, that age-hardening may be applied with decided advantage to alloys of this class.

The following figures have been obtained from propeller blades forged in the press, the alloy being slightly modified from the usual composition, without age-hardening, but with careful control of the crystal structure during the forging operations:—

Tensile strength	20-23 tons/in.^{2}.
0.1 per cent. proof stress	12-14 ,,
Elongation	5-11 per cent.
Wöhler fatigue range	± 7.5-± 8.5 tons/in.^{2}.

Higher strengths, with good elongation, have since been obtained.

Magnesium Alloys at High Temperatures

The strength of magnesium alloys falls off rapidly with increasing temperature, but the rate of fall varies greatly with the composition, so that a choice of alloys has to be made. For aircraft purposes, two ranges of temperature have to be considered. For crank cases a maximum of 150°C. may be taken, whilst for pistons a much higher temperature, 350°C. and even 450°, has to be considered. It is evident that heat treatments to give improved strength, other than a simple solution treatment to render the alloy homogeneous, are out of the question, as the working temperature will be high enough to undo their effect. The problem of finding suitable alloys then resolves itself into that of discovering structures of inherent strength at high temperatures, stable under prolonged heating or repeated intermittent heating and cooling. This does not necessarily mean using homogeneous solid solutions, as a network structure may be present, provided that it is not one which is absorbed and re-precipitated within the working range of temperature.

The required properties cannot be determined by simple tensile tests at high temperatures, using rates of loading similar to those of the ordinary tests. Creep becomes important, when the stress is continued for a long time. Few of the alloys have been tested under rigorous creep conditions, and the data available have been mostly obtained from accelerated tests. For the alloys containing aluminium, however, some general conclusions have been given (16). As with other metals, cast alloys have better creep resistance than forged, but by suitable heat treatment the structure may be made to approach more nearly to that of the cast alloy, whilst the precipitation of a constituent from solid solution during heating under load has a weakening effect.

In the course of tests at the N.P.L., aluminium, silver, manganese, calcium, nickel and cerium were found to strengthen magnesium, the strength-temperature curves being raised throughout their course, whilst combinations of two metals have a rather greater effect than one alone. Calcium is a useful addition for this purpose, with the added advantage that it is actually lighter than magnesium and that it improves the casting properties. So small a quantity as 0.35 per cent. has an effect. Cerium, in the order of 1 per cent., has a marked strengthening effect at 300°C., whilst when nickel is also added the hardness is similar to that of Y-alloy in the same range of temperature. Nickel, however, has the dis-

advantage of making the alloys very corrodible, and cobalt has given better results.* The following tests were obtained from forged material:—

Alloy.	Temp. °C.	Tensile Strength. Tons/in.²	Elongation %
Cerium 10 per cent. ...	20	18.6	0
Cobalt 1.5 per cent. ...	100	15.2	2.4
Manganese 1.5 per cent.	200	13.2	2.0
	300	7.4	15?

Cadmium, lithium, thallium, lead, zinc, tin, copper, and silicon were found ineffective as means of improving the properties at high temperatures.

Data as to the actual properties of the alloys under prolonged stress when hot are still rather scanty, and makers have been forced to use the rough guide provided by short-time tests at high temperatures. It is particularly in the neighbourhood of 140°C. that information as to the behaviour in creep is required, on account of the application to crank cases, etc. The suitability of the alloys for pistons is determined by a combination of qualities, of which resistance to creep is not the most important. Permanence of dimensions, resistance to fatigue, stability of internal structure (absence of changes leading to increased brittleness), thermal conductivity, are all properties of significance in this connection, and a more thorough study of these properties is essential. Pistons made of alloys similar to those mentioned have, however, given excellent results in trial runs under overload, and it is probable that improvements in composition are the best means of obtaining better performance.

The coefficient of expansion of light magnesium alloys with rise of temperature differs little from that of the more usual alloys of aluminium, containing copper. The expansion of metallic magnesium is given by the formula (17):—

$$l_t = l_0 \left[1 + (24.80\, t + 0.00961\, t^2)\, 10^{-6}\right]$$

and this is little affected by additions of aluminium or manganese. Extruded alloys show a slightly lower coefficient than cast, but the difference is small. The following values are given by the same authors:—

20-100°	Cast 26.1×10^{-6}	Extruded 25.8×10^{-6}
20-200°	27.0	26.8
20-300°	28.0	27.8
20-400°	28.9	28.8

The figures given by the makers of the Elektron alloys are, however, slightly lower, namely:—

20-100°	Cast 25.6×10^{-6}	Forged or rolled 24.0×10^{-6}
20-200°	27.1	25.4

The thermal conductivity is much the same for the various alloys in general use, being about 0.32 KCals./c.c. Among the experimental alloys tested at the N.P.L. cerium was found to lower the value, an alloy with 10 per cent. of cerium giving 0.25, whilst one containing cerium, cobalt and manganese gave 0.31 KCals./c.c. The conductivity at 250°C. is the same as that at 20°.

An obvious difficulty in the use of alloys of magnesium is their ready corrodibility. Magnesium is a highly reactive metal, which can even decompose water. No addition of an alloying metal, in quantities within the range of the light alloys, will inhibit this corrosion, although the influence of small quantities of manganese is known to be favourable. The effects of different metals vary, some increasing the corrodibility to an intense degree. Actually, however, the resistance is greater than might have been expected. A simple film formed by exposure to air affords some protection, so that a specimen left in the open in a fairly clean atmosphere will only show a thin white crust when a piece of iron exposed at the same time is thick with rust. The fact that iron rusts easily does not prevent its use, and both metals must be protected by some kind of coating

* Patent Application No. 12658, 5/5/36.

against atmospheric attack. Lanoline affords some protection, but it is usual to employ a chemical treatment with the object of forming an adherent protective layer, united chemically and not merely mechanically to the metal. Three such treatments have been devised, using chromate, fluoride, and selenium respectively. The subject of protection has been very fully discussed by Bengough and Whitby (18), and by Aitchison (1), and there has been little further development since their papers. The fluoride and selenium processes do not seem to have got beyond the experimental stage as yet, and the industrial processes in use all involve the production of a chromate film in one way or another.

The production of a chemical film is intended not only to protect by itself against atmospheric attack, but to serve as a basis to retain a coating of varnish, paint, or enamel. Paints, etc., do not adhere to the bare metal without such treatment. Of the possible pigments, zinc chromate appears to offer the greatest advantages, although zinc oxide is also useful (19). Lead compounds must be avoided, as if any reduction should take place, an intense electrolytic local couple would be set up between magnesium and lead.

A peculiar example of corrosion, of special interest to the aircraft industry, is the attack of leaded fuels on petrol tanks made of sheet magnesium alloys. A full account of the mechanism of corrosion has been given in a recent paper to this Society (20), in which it was shown that neither lead tetra-ethyl nor ethylene dibromide attacks magnesium, but that when both are present, together with water, reactions can take place which result in the deposition of lead, with the electrolytic effects mentioned above. Some organic substances inhibit the attack without impairing the anti-knock qualities, notably quinoline when added to the extent of 1 per cent. Another plan of protection depends on inserting a cartridge containing some salt which will absorb water, as the dry components of leaded fuel are without action. Such a salt is potassium fluoride, which takes up water and forms a protective deposit, but chromates are also used.

Chlorides accelerate the corrosion of magnesium and its alloys, and tend to break down any protective film on the surface. For this reason, atmospheres near the sea, which contain suspended particles of salt, are particularly harmful, and a structure which will behave well in an inland climate will suffer badly when used in a seaplane, or even in an aeroplane in this country, where the island climate involves the constant presence of such particles in winds coming from the sea. An inert varnish of some kind is then essential, as well as the chemically prepared coating. Excessive corrosion was found in some large industrial structures, owing to imperfect separation of the flux from the metal during casting. Particles of flux or slag containing chlorides, if embedded in the metal, set up centres of intense local corrosion, leading rapidly to complete destruction. The greatest precautions have therefore to be taken in making ingots or castings, to avoid the entrapping of flux. This also applies with special force to welded structures, a matter which was fully dealt with by Dr. Aitchison (1). He recommends brushing the finished weld with hot water containing 15 per cent. of potassium dichromate until all the flux has been removed.

The protection of the surface of airscrews presents a specially difficult problem. Here it is not so much a question of chemical corrosion, as rather of abrasion of the leading edge by dust particles and rain drops, in consequence of the high velocity. When the air contains salt particles also, this action is greatly accelerated. Marked differences are found between different climates in this respect, which are not completely accounted for by the prevailing winds and the nearness to the sea. Even the very adherent coating produced by the chromate treatment suffers under abrasive conditions, and paints and enamels prove inadequate. Treatment with chromate, followed by lanoline or a varnish with a base of Tung oil, affords as much protection as can be expected, but there is room for improvement in this direction. Where the air is charged with fine particles of sand, as in Iraq, the abrasion is such as to put metal airscrews out of the question, at least until a more perfect method of preserving the surface has been devised.

The ideal surface to resist such severe abrasion would be a hard metallic coating, preferably of chromium, and this is the direction in which success is likely to be found. To deposit chromium directly on a magnesium alloy is almost certainly impracticable, but the production of intermediate metallic coatings, free from pinholes and capable of receiving an electrolytic deposit of chromium, seems to be promising, and some success has already been obtained. Emphasis is laid on the freedom from even minute pinholes, as chromium, whilst forming without difficulty an impervious layer, has no power of filling up holes in the underlying layer, so that every imperfection is faithfully reproduced. The presence of such pinholes leads to corrosion and to stripping.

Certain alloys of aluminium fall to be mentioned in this connection, in which magnesium is the alloying element. With from 5 to 15 per cent. of magnesium alloys are obtained with tensile strengths up to 28 tons in.$^{-2}$, with large elongation. These alloys are readily rolled into sheet, the structure being the cubic one of aluminium and not the hexagonal of magnesium. They are also used as castings and as forgings, being remarkably resistant to the action of sea water. Any tendency to inter-crystalline corrosion is overcome by a heat treatment which brings all the alloying metal into solid solution. Those with the higher proportion of magnesium are very sensitive to changes of heat treatment.

In the preparation of this paper which is intended merely as a basis for discussion, I have made use of a monograph on magnesium prepared in this laboratory by Dr. J. L. Haughton and Mr. W. E. Prytherch shortly to be published by H.M. Stationery Office. I am also indebted to Mr. W. C. Devereux of Messrs. High Duty Alloys, Ltd., Slough, for much useful discussion and for photographs, and to conversations with other friends connected with the magnesium and aircraft industries, as well as to Messrs. Short Bros. for photographs. All who have had occasion to study the question must also acknowledge their indebtedness to the valuable papers of Dr. W. Schmidt.

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Discussion.

Major Buchanan: The Society had listened to a most instructive and interesting paper, which he hoped would give rise to a good discussion. It was unfortunate that the work on the new magnesium alloys had not proceeded sufficiently far to be included in the paper, but such information as it had been possible to give excited their curiosity, and perhaps Dr. Desch would, at a later date, be able to come to the Society and describe some more developments in this direction.

The use of magnesium alloys in aeronautical engineering was increasing steadily, though at a pace which was much slower than many of them would like to see. More use was being made of these alloys in Germany than in this country, and workshop technique there had been extensively developed. He hoped that this paper would stimulate aeronautical engineers in this country to a closer investigation and a more extensive use of these valuable materials. The susceptibility of these alloys to corrosion, had, for many years, been a serious obstacle to their use. The introduction of the chromate treatment had improved matters very considerably, and had reduced the liability to corrosion to such an extent that the material was satisfactory even for use in ship planes—that is, planes used from the deck of ships. Many of those present might know that the aeroplane wheels used in the Air Force were made of magnesium castings, and even after years of service at sea did not show enough corrosion to render then unserviceable.

With regard to the use of magnesium alloys for airscrew blades, experience with these in flight in this country on landplanes had not resulted in sufficient erosion to cause apprehension, but one could imagine that airscrew blades of magnesium alloys used in seaplanes or in planes in desert countries might show somewhat extensive deterioration. He called upon Mr. Pye to open the discussion.

Mr. D. R. Pye (*Fellow*) : He desired to exercise his privilege as the opener of the discussion to express on behalf of the audience, the thanks of the Society to Dr. Desch for his extremely interesting lecture. The Chairman had mentioned that the Society was fortunate in the way it had been able to persuade distinguished experts to come and talk at its meetings. It was almost a year since Professor W. L. Bragg had given a lecture on the theory of alloy structures. He was not sure how many of the audience on that occasion really understood very much of the lecture, and indeed, Professor Bragg had told them that he doubted whether it was possible for anybody who had the engineering point of view to understand wave mechanics, but he himself still remembered it vividly, as a lecture which was most stimulating, and which gave one a peep into that mysterious world where the rules and regulations as to why some metals alloyed with one another and others did not, were disclosed.

Dr. Desch had talked to them that evening in a way which again had emphasised the great importance of an understanding of atomic and crystal structure when one was seeking to promote the improvement of the mechanical properties of alloys, and before he turned to what he might call the positive results of the work for which Dr. Desch had been responsible, he wished to point out the extreme importance of having men capable of focussing scientific knowledge on problems of this kind even when it was only negative results that were being sought. Negative results could be of inestimable importance at times. He instanced the case of beryllium, a metal which was superficially extraordinarily attractive. Dr. Desch at the beginning of his lecture said that from many points of view beryllium and magnesium might be expected to make a satisfactory alloy, and yet nobody, so far, had been able to produce one. He then went on to say that when the atomic sizes of these two materials were studied, one began to see the reason for that. If it were not that one could bring to bear that kind of fundamental knowledge of atomic diameters on to problems of this kind, one would always be in the position of feeling that around the corner might be something extraordinarily good, so that a great deal of money might be spent in searching for what could never be found. It was desirable, therefore, to understand the importance of really reliable negative information, and it seemed to him that in metallurgy and the study of alloys the bringing to bear of the most fundamental scientific knowledge on a problem of this kind was of the highest importance.

To turn to the positive side of what Dr. Desch had been telling them, it was about five years ago that the Air Ministry had come to the conclusion that if the possibilities of magnesium as a light metal in aircraft construction were to be properly exploited, some really intensive work by the best qualified laboratory in

the country was necessary. The Department of Scientific and Industrial Research was approached, and, as a result, the study of magnesium alloys as they were then known, and the possibility of their improvement, was placed on the research programme of the National Physical Laboratory.

The objectives of that work might be divided into three groups: (1) Alloys at normal temperatures for such use as airscrew blades; (2) Alloys at moderate temperatures (up to 150°C.); (3) Alloys at high temperatures—Dr. Desch had mentioned 350°C., but he thought that pistons now might reach temperatures more like 450°C. He thought there was no doubt at all from what they had heard that evening that substantial progress had been made in each of these directions. Dr. Desch had spoken of a forged or pressed alloy with an ultimate strength of 27.6 tons per square inch, which was the kind of figure one associated with duralumin, a " 0.1 per cent. proof stress " of 19.5, and an elongation of 4.2 per cent. Those results were quite outstanding. In the direction of the crank-case alloys for use up to 150°C., not much was yet available in the way of results of practical tests; but as regards the piston alloys, he thought he was right in saying that at about 250° to 300°C., there were indications that the mechanical properties of the new magnesium alloys were actually superior to those of Y alloy, the type of material at present largely used for aircraft engine pistons. The essential difficulties of magnesium as a starting material had been emphasised by Dr. Desch. It was extremely active chemically and, hence, corrodible. On the corrosion side the development of these alloys had been assisted by co-operative work between the National Physical Laboratory and the Royal Aircraft Establishment, where a special study had been made of the corrosion of magnesium alloys and methods for its prevention.

One last point which he desired to emphasise was the way in which the manufacturers had come forward with the greatest possible readiness to assist in the technical stage of the development of these alloys. There had been a very close co-operation between the National Physical Laboratory and the members of the metallurgical industry who had large presses and forging facilities. It was not until new alloys of this kind were tested on the industrial scale that any one could say how useful they were ultimately going to be. Owing to the co-operation which had been forthcoming from the very earliest stages, he hoped and believed that there was no likelihood of any repetition of what happened in the case of an earlier development, before Dr. Desch's time at the National Physical Laboratory. He was not sure at what date Y alloy was first produced at the National Physical Laboratory, but he thought it was as early as 1917, and for something like ten years that alloy lay dormant as an interesting piece of academic research. Nowadays, it or slight modifications of it were universally used for the highest duty engine pistons. In present circumstances, he was glad to feel confident that at the earliest moment when any of these alloys were ready for industrial development the producers of magnesium and aluminium alloys would be ready to make the best possible use of them.

Mr. DEVEREUX (*Fellow*): He was glad to have this opportunity of mentioning the debt of the magnesium industry to the work of Dr. Desch and his colleagues at the National Physical Laboratory. He doubted whether, as one engaged in actual manufacture, he could add much to the discussion. Any discussion would better come from those using the material. But as Dr. Desch had mentioned beryllium alloys in connection with aluminium, he would like to know whether his statement, that there was hardly likely to be useful outcome of that investigation, applied to the high beryllium end of the beryllium-aluminium series.

Dr. Desch had given some interesting figures concerning heat-treated magnesium alloys, and some interesting figures were also being obtained from test pieces, but he thought the reason why the heat-treated alloys had not realised the hopes which attended their introduction had still to be sought. There had been unfortunate cases where heat-treated castings had worked successfully on initial engines, but on production had failed to such an extent that they had to be

put on one side. He felt that this was due to something inherent in the material which had to be overcome, and that it was not related to the actual heat-treatment. Perhaps it was the beautiful looking appearance of magnesium castings on machines that had led them to believe that they were free from porosity, but he felt that there was an inter-endritic type of porosity which restricted the heat-treatment phenomena, and it was for that reason these inconsistencies arose. It would be interesting to know whether Dr. Desch agreed.

There was one other point in the work they had done which led them to believe, that in addition to the work on the alloy and its composition, an increasing amount of investigation was necessary on the actual working, particularly in those alloys where a search was made for creep characteristics. It could fairly be said now that on those alloys such as piston alloys where creep played such an important part, the hammer and the stamp were likely to assist a great deal.

Another part of the subject on which the works industry particularly needed further information was that of damping capacities, and their relation to the variation of stresses between alloy and alloy. These considerations would play an important part in such things as propeller blades, where now the aircraft manufacturer was centreing solely on fatigue properties.

Dr. Desch referred to abrasion by dust particles, and said that where the air was charged with fine particles of sand, as in Iraq, the abrasion was such as to put metal airscrews out of the question. Dr. Desch did not apparently discriminate between aluminium alloys and magnesium alloys, and that rather led him to believe that the attack was very similar, and was scarcely worse in magnesium than in aluminium alloys.

Dr. Sutton (*Fellow*): Dr. Desch had a unique knowledge of matters of this kind and was one of the leading authorities on the chemistry of alloys. He had been particularly interested in his remarks on the sources and extraction of magnesium. Dr. Schmidt had claimed that magnesium in Germany was cheaper to produce than aluminium, there being no expensive preparatory treatment of the raw material as compared with the treatment of the material necessary in the extraction of aluminium. He had further stated that the energy consumed in extraction per kilogram of magnesium was not greater than in aluminium, while the bulk produced per kilowatt hour was 50 per cent. greater than with aluminium. His comparison appeared to be made on a volume basis, but perhaps that was to be justified when considering these materials in relation to aircraft structures.

Was it possible to look for cheaper magnesium?

Dr. Desch had referred to the ready corrodibility of magnesium alloys. During the last ten years, the change in the properties of magnesium and magnesium alloys which had impressed the speaker most had been the improvement in corrosion resistance. Dr. Schmidt told of an early sample which was sent by ordinary means of transport on no very long journey, and on arrival at Friedrichshaven had to be cleaned free from corrosion products. The modern material was very different from that, and Dr. Schmidt attributed this to the freedom from oxides and nitrides in modern magnesium as a result of treatment. It was also customary to add a small amount of manganese to the alloys, and this appeared to be of considerable benefit. With regard to resistance to marine atmospheres, the best present alloy still stood considerably below the best aluminium alloys, and it would be interesting to hear Dr. Desch's views on the next step that should be taken in the endeavour towards a corrosion-resisting magnesium alloy.

Dr. Desch's remarks on recent experience with wrought alloys showing up to 22 per cent. elongation was very encouraging. In aircraft work, they had an admirable selection of aluminium-rich alloys, but in the case of magnesium the cold bending had to be around a radius of something of the order of 10 or 12 times the thickness. Although this limited workability of magnesium alloys was thought by some to be over-rated, it would give a big impetus to the use of

magnesium structures in aircraft if a cold-working alloy were forthcoming. The figures Dr. Desch had laid before the Society were the most promising he had seen in that connection.

He desired to draw attention to two small points which to him were rather paradoxical. Dr. Desch had referred to an atmosphere rich in sulphur dioxide as a necessity during annealing processes. Magnesium burns with much greater rapidity in sulphur oxide than in air. It might be that it was difficult to ignite, but once ignited it burned extremely powerfully in sulphur dioxide, and that was not surprising, because sulphur dioxide contained 100 per cent. of its own volume of oxygen, and air only 20 per cent.

With regard to the use of fused chromate salts, he would only mention that if they were taken up to a temperature sufficient to melt magnesium there would be a rather good firework display.

Major BALL: As one connected with the production and distribution of magnesium, he had come prepared to welcome comments from consumers rather than to say anything on his own account, but he might add a word on a matter touched upon by Dr. Sutton. Dr. Schmidt in his paper gave very interesting statistics relating to the production of magnesium in Germany; but in Germany they had a certain definite physical advantage. They had a supply of essential raw materials such as, unfortunately, was not available in this country, and which helped considerably to cheapen their process. His Company—Magnesium Electron, Ltd.—believed, however, that they would very nearly attain to German production costs at the new works which was now starting production of metal near Manchester, but it was too early yet for them to commit themselves to any definite figure. He was as firmly convinced as Dr. Schmidt that the day was not far distant when the present prices of magnesium alloys would be materially reduced. They would have to be reduced if the material was to find that consumption which its qualities justified.

As a matter of interest, he could go so far as to say that their experiments in the field of direct production from dolomite had proceeded much more quickly and with greater success than had been anticipated. A trial plant ought to be running by April or May of this year, and if the figures which it was believed could be obtained from that plant were actually forthcoming, then it should be possible to produce magnesium from their own supplies of dolomite in this country, avoiding any necessity for the shipping of raw materials, and it was also believed that this might be done at a figure lower than the present costs of electrolytic production.

Mr. W. O. MANNING (*Fellow*): Professor Desch had stated that molten magnesium had very little power of dissolving gases, but a little later in the paper he said that the metal absorbed not only oxygen but also nitrogen with avidity. Ought he to read the word " absorbs " as meaning " chemically combines with "?

Dr. DESCH: That should be the reading.

Mr. DAVIES: He would like to ask a question as to the figures for different alloys which Dr. Desch had given. Was it likely that there would be available material in either sheet form or extrusion similar to duralumin, or the higher grades of aluminium alloy, and suitable for general use not on the engine side but on the aircraft side? If such a thing were possible it would simply revolutionise the present ideas of structural weight.

Dr. Desch had pointed out the high extensibility of magnesium alloy. That might not be such a big disadvantage, because he thought Young's modulus of aluminium bore the same relation to its specific gravity as Young's modulus of, say, steel or magnesium. In fact, there seemed to be a close relationship between all three materials in this respect.

Another interesting point was that the ultimate strength-weight ratio of steel and aluminium bore a close relation. Apparently magnesium had a higher ratio.

Reply to the Discussion.

He thanked Mr. Pye for his remarks and his useful information. With regard to pistons, he had used the phrase "a temperature of 350°C. or more." He knew that higher temperatures were talked about. Obviously, a temperature of 450°C. was a very difficult thing for a new alloy to meet.

In reply to Mr. Devereux's questions, he knew really nothing about these high beryllium-aluminium alloys. The work on beryllium at the N.P.L. was practically concluded at the time he went there. One heard rumours now and then of wonderful results, but he had never been able to get hold of the alloys or of actual figures. The only reference he had given in his paper was one dated a number of years ago —1929—when it was claimed that very good results had been obtained. Whatever developments had occurred since 1929, when Dr. Gillett gave his description, had not been made generally known.

He was interested to hear about the failure of some of the heat-treated castings. Evidently the question of inter-dendritic porosity had to be dealt with. But that probably arose from the fact that the coefficient of expansion of magnesium crystals was different in different directions, so that there was a tendency for the crystals to shrink away from one another. Possibly some means of compression during freezing to prevent that porosity might have to be adopted. It was not out of the question to deal with that.

With regard to his remarks about abrasion, his information was that all metal airscrews suffered badly from such conditions as he had indicated, and that non-metallic materials stood up much better.

Mr. Sutton had put a question as regards relative prices which he could not answer in the least. It was perhaps worth noting that in the interesting series of articles in the *Metallwirtschaft* dealing with the Goering four-year plan, stress had been laid on the enormous development of the aluminium industry in Germany, but in the issue that appeared, he thought, a fortnight ago, the remark was made, "We do not appear to be at present able to count very greatly on the expansion of magnesium to fill the gap." That was the only reference of the kind he had seen in these discussions.

It would be very interesting if other metals could be found, which, added in small quantities to magnesium, would behave as manganese did, and offer increased resistance to corrosion, but so far as it had been tested he did not think anything had been found to work as well as manganese.

Magnesium was an extremely electropositive metal and had a great tendency to form compounds which were reactive. For example, the compounds of magnesium with lead and tin were actually decomposed by water, they were so reactive.

As regards the paradox that magnesium burned readily in sulphur dioxide, he thought the fact was that the gas did not come into contact with the metal, there was a film layer, and the sulphur dioxide kept out the oxygen which would react very readily, while it did not come sufficiently in contact with the metal to cause the actual combustion.

[*Added later.*] It was probable that a certain temperature was necessary to start the combustion. Magnesium already burning would decompose sulphur dioxide, whilst at a lower temperature the gas was inert.

He was interested to hear of the further prospects of supplies of magnesium in this country. As to whether there was a prospect of alloys being made, which, in the sheet or extruded form would be quite serviceable, he saw no reason why this should not be done. It was simply a question of improving the technique of working. The difficulty was to get rid of the preferred orientation; if this were destroyed it should be possible to get alloys capable of cold working.

The relation between Young's modulus and density had to be borne in mind, but one could not simply alter the whole design of a structure to take full advantage of the extra lightness. There were other considerations that came in. In

order to obtain stiffness, it might not be possible to reduce the sections to the extent one would predict, simply from the relation between strength and density. Therefore, he thought a low Young's modulus was definitely a disadvantage. Whether the relation between Young's modulus and density was a general one, he would not like to say. If it were true, then the statements as to the very high Young's modulus of beryllium could not be correct. This was a metal quite different from magnesium in character, and the statements about Young's modulus might be based simply on calculations which were not justified.

On the motion of the Chairman, a hearty vote of thanks was accorded to Dr. Desch.

AT HIGH ALTITUDE.*

By F. W. Lanchester, LL.D., F.R.S., *Hon. Fellow.*

Part I and Appendix I.

Summary.

In the present paper it is demonstrated that variations in the Reynolds number as due to altitude are unimportant, provided that $\mathbf{N}_E$ at sea level is in the region of 10^7.

That under these conditions the law of velocity in relation to altitude, is implicitly contained in the expression $W = K_L \rho V^2 \times$ area, in which ρ and V only are variables; *i.e.*, the velocity of flight must vary in the inverse ratio of $\sqrt{\rho}$.

That the velocity limit due to the elasticity of air is lower at high altitude, for (1) the velocity of sound is lower, (2) the optimum flight velocity is higher. The facts concerning this are set forth.

The relation between the *optimum condition*, as determining the design for least resistance, and the *condition of least resistance* for a machine "in being," is made clear. Graphs are given showing the relation of velocity to altitude under the condition of span = constant. These are referrrd to as K-span graphs.

Following this a method is demonstrated by which graphs of constant power —K-power graphs—are evolved and the final result is represented in the form of a chart relating to a hypothetical aeroplane of four tons gross weight and of aspect ratio = 10, in which four interdependents are represented in their correct relationship, namely, *altitude*, *velocity*, *optimum span*, and *net thrust h.p.*; any two of these being given the other two are determined.

§1. The Nature of the Problem.

The subject of high altitude flying is often spoken of as one of which the theory is not well understood. In the discussion of the author's recent paper on "The Part Played by Skin-Friction in Aeronautics" the fact came to light that many of those technically engaged in aeronautical engineering are not altogether clear on the subject of the economics of flight at moderate and low altitudes; this may account for a great deal.[1]

For the sake of simplicity we will in the first instance consider the case of a bodiless glider.[2]

The fundamental principles are precisely the same regardless of altitude. The theory of least resistance stands, as set forth in "Aerodynamics" and in Part IV of the author's recent paper, and the diagrams giving the relation of K_D to K_L and K_D/K_L apply to high altitudes as to low. It will now be shown that the fact that ρ (the density of the air) enters into the equations, is all that is necessary to take charge of variations of altitude.

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* Part II relating to the power plant will be published in the June issue of the Journal.

[1] C.f. Journal Aeronautical Society, February, 1937, p. 114, lines 9 *et seq;* and p. 124, lines 23 *et seq.*

[2] The resistance of the ancillary organs—the tail plane, elevator, rudder, etc.—present a "wetted" surface commonly equal to about 25 per cent. that of the aerofoil; this must be taken into account as variable, *i.e.*, as giving rise to part of the aerofoil direct resistance. An addition of 25 per cent. to the value of C_0 is all that is necessary.

From fundamental considerations we know that K_D/K_L for least resistance is independent of the density.[3] In the equation, $W = K_L \rho V^2 a$, if we stipulate that the weight W and aerofoil area a, are prefixed;[4] then for given K_L (opt.) corresponding to least gliding angle, ρV^2 is constant, that is to say, with change of altitude $V \propto \sqrt{\rho}$, this is as given in the author's recent paper,[5] App. IV. Thus if we decide to fly under optimum conditions, at all altitudes the relation of velocity to altitude will be as plotted in Figs. 1A[6] and 1B, where $V \propto 1/\sqrt{\rho}$; under these conditions the net drag will be the same for all altitudes.

§2. The Question of Reynolds Number, N_R.

Since a change of altitude gives rise to a temperature difference it involves a change of viscosity μ; moreover, the density ρ is not constant and thus kinematic

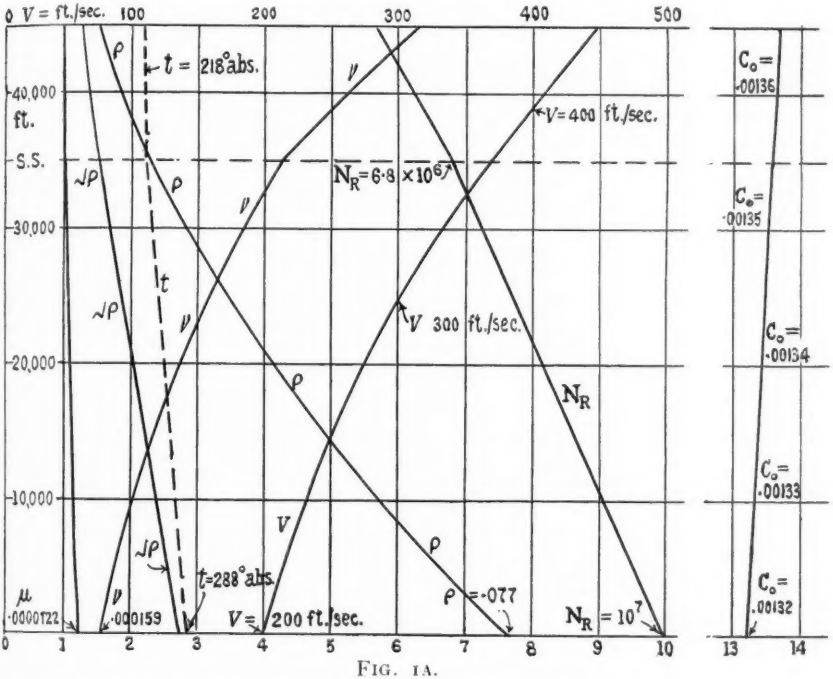

FIG. 1A.

Illustrating the derivation of the K-span graph, V varies as $1/\sqrt{\rho}$, also the influence of altitude as affecting the Reynolds number, and the constant C_0. Units ft./lb./sec.

viscosity ν (the expression for which is μ/ρ) is a function of altitude. Again, since the velocity of flight, V, under optimum conditions, varies as $1/\sqrt{\rho}$, N_R the Reynolds number, LV/ν is a function of altitude.

In Figs. 1A and 1B the values of temperature t and ρ are plotted as functions of altitude, these are the accepted values for the average or "International

[3] As in the author's paper "The Part Played by Skin-Friction in Aeronautics" (Journal, February, 1937), Part IV, the *high* Reynolds number is assumed.

[4] The aeroplane here is taken as a thing "in being" and assumed not to undergo any change.

[5] *Loc. cit. ante.*

[6] Based on the "International Standard" atmosphere. In Fig. 1A the plottings are in ft./lbs./sec. units and Fig. 1B in terms of c.g.s. In both temperature is expressed in degrees C.

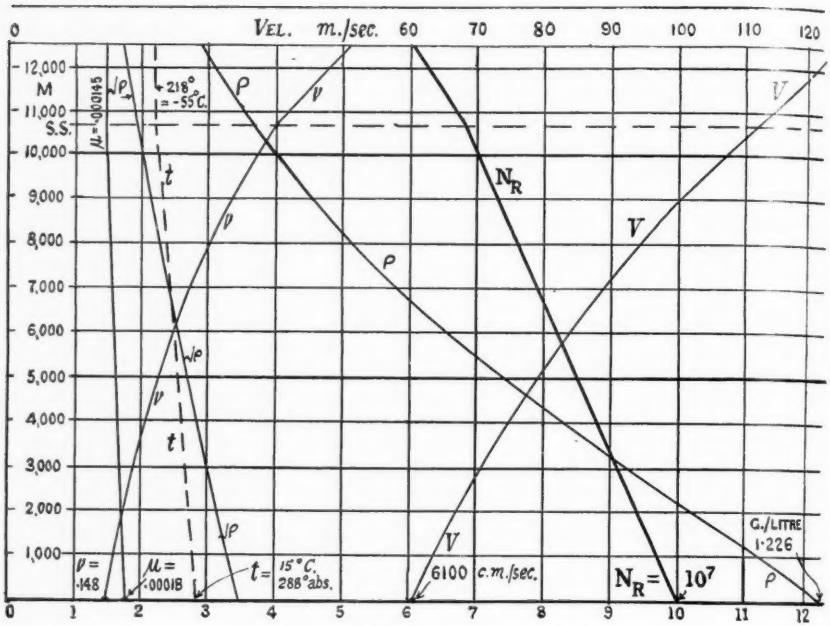

FIG. 1B.

As in Fig. 1A, but Units c.g.s

standard " atmosphere,[7] the temperature at sea level being assumed = 15°C. (= 288° absolute); this is known to decrease steadily up to = 35,000ft. = 10,700 metres. At about that level the stratosphere is reached in which the temperature stands nearly constant, approximately − 55°C. (= 218° absolute). This is clearly shown in the plotting. The graph giving ρ as a function of altitude is also plotted as defined by the standard atmosphere, the datum value at sea level is taken as 0.077 lbs./cu. ft., or 0.001226 gram/c.c. at 15°C. From the values of t, a graph representing μ the viscosity of air (as related to temperature), is plotted. From the given values of ρ a graph $\sqrt{\rho}$ is plotted, and from this, the graph representing V the flight velocity appropriate to the altitude is derived ($V \times \sqrt{\rho} = \text{const.}$). From ρ the density and μ the viscosity, values of ν are calculated and the graph plotted; we are then able to give $\mathbf{N}_R = LV/\nu$ in the form of a graph as a function of altitude. To effect this we must assume a value of V at sea level, and of L a linear parameter, the chord dimension of the aerofoil. In Figs. 1A and 1B, V at sea level has been taken as 200 ft./sec. (= 6,100 c.m./sec.) and the value of L = 8ft. (= 244 c.m.), giving $\mathbf{N}_R$ at sea level = 10^7. It will be seen that this falls steadily[8] to 6.8×10^6 when the stratosphere is reached; after that the rate of fali is more rapid. At the extreme right (Fig. 1A) will be seen values[9] of $\mathbf{C}_o$ corresponding to the values given of $\mathbf{N}_R$; the total variation is approximately 3 per cent. Thus we may conclude that the variation in $\mathbf{N}_R$ is of no material importance as concerns the dynamics of

[7] See Appendix II.

[8] The N_R graph is sensibly straight, although there is no obvious reason why this should be so. Both N_R and C_o being dimensionless constants have the same value in Fig. 1A as in Fig. 1B.

[9] Taken from the graph given in Fig. 2 of the author's recent paper.

flight at high altitude, the Reynolds number at all altitudes is well above the critical value.

That this may not always be so must be admitted; for example, in the case of a glider whose normal value of $\mathbf{N}_R$ is only just about the lower limit, say 1.5×10^6, the value at 40,000ft. altitude will fall below 10^6 and prediction from theory (or even from experiment) becomes unreliable. But in the case of an aeroplane of three or four tons weight, the sea level value given in the plotting, namely, 10^7, cannot be far from the truth.[10]

With reference to the value of $\mathbf{C}_o$ (to which the frictional drag is proportional) this, as shown by the graph, is increased less than 3 per cent. in passing from sea level well up into the stratosphere; allowing for an "adjustment"[11] in the form of a slight reduction of velocity this will result in less than $1\frac{1}{2}$ per cent. increase in net resistance; which is negligible.

§3. Body Resistance.

We have now from the same standpoint to consider body resistance. Resistances in this category vary as the square of the velocity and directly as the density,[12] that is to say, as $V^2\rho$, and so are constant. If this resistance were to depend wholly on skin-friction (and this is the modern trend) it will also be affected by a change in the value of $\mathbf{C}_o$; but owing to the greater length in the line of flight, the parameter L, on which depends the value of $\mathbf{N}_R$, is about five times greater than that of the aerofoil. This means that $\mathbf{N}_R$ will be greater and the increase of resistance due to the increase of $\mathbf{C}_o$ with height will accordingly be less—more nearly in the region of 2 per cent. for 35,000ft. altitude. This is not subject to any "adjustment,"[13] so that we may say, as concerns the whole aeroplane, that, if we neglect influences due to change of $\mathbf{N}_R$ with altitude, the error introduced will be certainly less than 2 per cent. of the total resistance, which it is not such as a pilot would notice. *We therefore dismiss the influence of altitude on the values of* $\mathbf{C}_o$ *as requiring no further consideration.*[14]

The main conclusion so far reached is that if we take an *actual* machine of weight W, whose aerofoil is of fixed area and form, in brief a machine "in being," and vary its velocity of flight in inverse ratio to the square root of the atmospheric density *its resistance will be constant in respect of altitude.*

§4. Altitude as Affecting the Velocity of Sound.

Before proceeding one reservation must be made. To consider quantitatively the influence of the elasticity of the air is not yet possible. It is usually assumed that provided the velocity of sound is not too nearly approached the effect of elasticity may be ignored, and no ill effects have so far been found to result from this assumption. The weak point in this respect is the propeller; the velocity of the blade tips in a modern high speed machine is sometimes found to exceed the limiting value, which, with the velocity of sound = 1,140 ft./sec., is in the region of 900 ft./sec. At high altitude the velocity of sound is less than at sea level owing to the lower temperature; it falls to 970 ft./sec. at 35,000ft. about the lower limit of the stratosphere and thus the influence of elasticity may become appreciable at a blade tip speed in the region of 750 ft./sec. This under optimum conditions at sea level gives 400 ft./sec. To be more explicit, if an aeroplane whose blade tip speed at sea level were 400 ft./sec. were flown under optimum conditions at 35,000ft. altitude (the lower limit of the stratosphere) the tip speed will be 750 ft./sec. and, at any higher velocity, the influence of compressibility might be found serious. When in doubt experiment alone can decide.

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[10] C.f. "The Part Played by Skin-Friction in Aeronautics," Appendix II, Fig. 23.
[11] To the optimum condition.
[12] The form of equation $R = K\rho V^2 a$ applies.
[13] It is nevertheless subject to a reduction on account of the fact that part only of the resistance is due to skin-friction.
[14] An allowance may be made if wished.

Since the temperature within the stratosphere is approximately constant,[15] the velocity of sound above 35,000ft. may be regarded as uniform, namely, 970 ft./sec.

§5. Velocity and Area Variable, Density Constant.

Making use of the same equation as previously, namely, $W = K_L \rho V^2 a$, we will now examine the condition when flying at some definite altitude; that is to say, the density is deemed constant. The two variables with which we are now concerned are the velocity and the area. It is assumed that the form of the aerofoil is subject to the laws of similarity and the area is controlled by a linear

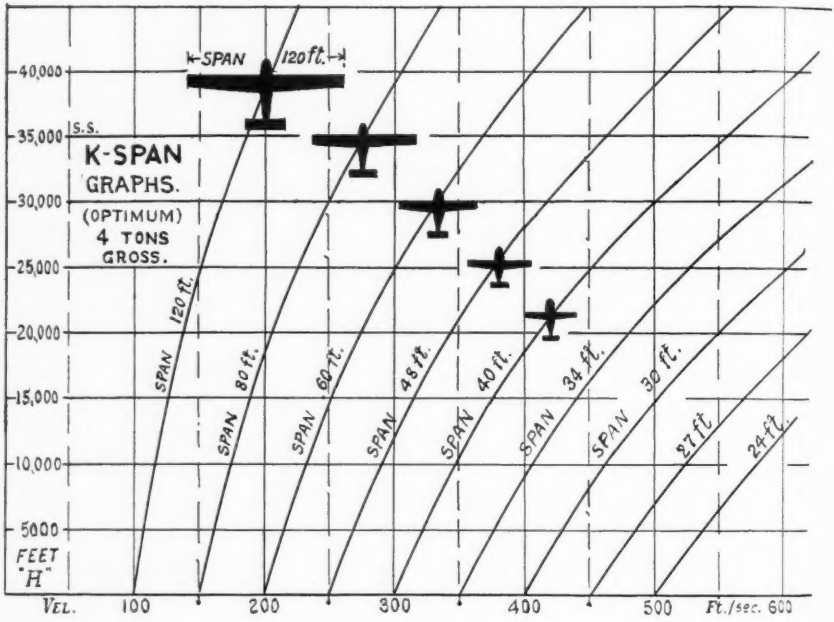


Fig. 2.

The figure gives the appropriate span in feet for an aeroplane of four tons gross weight, having an aspect ratio =10; for altitudes up to 45,000 ft. The span appropriate to each K-span graph is also illustrated by silhouettes drawn to scale. Bearing in mind the normal facilities for taking off and alighting, for a machine of the weight given, a span of less than 40 or 50 feet would give far too high a loading; this at present restricts the optimum condition in its application. If, by an increase in the size of the aerodromes, or other means, the taking off and alighting speed permissible could be increased, this restriction (in some degree) might be relaxed.

parameter, to express this we may make use of the span S. Then area varies[16] as S^2, and we have therefore V^2S^2 = constant, which establishes the relation S varies inversely as V.

Thus if we choose a number of values of V, say at sea level, then for optimum conditions for each velocity there will be an appropriate span. If now in each particular case we take a to be constant and ρ variable (as in Figs. 1A and 1B) then we shall have a number of graphs of similar character, in all of which the

[15] This is generally speaking assumed.

[16] It is taken $=S^2/n$ where n is aspect ratio as defined, Appendix II of Paper, *l.c. ante.*

velocity varies with altitude inversely as $\sqrt{\rho}$, and each of these graphs will relate to some particular span, this is illustrated pictorially in Fig. 2. These graphs, each of which relates to a definite span, will be hereinafter termed *constant span*, or for short, *K*-span graphs.[17] The quantitative or numerical relations between velocity and span and the other quantities included in the equation will be dealt with later.

§6. The Paradox.

The author has used the term *optimum condition*. This may be defined as that under which the resistance due to aerofoil and ancillary surfaces,[18] but not including body resistance, has a minimum value, that is to say, when their aerodynamic resistance, or drag, is equal to their direct or skin-frictional resistance.[19] This resistance is, as the author has shown, constant and independent of velocity.[20] On the other hand, the *velocity of least resistance* is that when the aerodynamic resistance is equal to the total direct resistance *including that of the body*.[21] The distinction between these two conditions has from time to time been the cause of a little confusion. To many it seems strange and paradoxical that the velocity of least resistance should be other than the optimum condition. The author, in Appendix IV of his recent paper,[22] endeavoured to make this clear, but he is not quite sure whether he succeeded in making plain the nature of the distinction. The two conditions were clearly enunciated in Props. I and IV in the author's "Aerodynamics," and on more than one occasion he has found himself accused of inconsistency. It is, therefore, necessary to treat this matter as a paradox which has to be elucidated.

Let us suppose that an aeronautical engineer be instructed to design a machine of weight W whose resistance shall be a minimum *at some stated velocity* V_2 the body being already specified to comply with the service contemplated. Then he must proportion the aerofoil to give least resistance for that particular velocity as shown by the graphs x and y representing respectively the direct and aerodynamic resistance of the aerofoil which intersect at the value V_2 (Fig. 3), this defines the *optimum* condition. But a pilot flying such a machine, if short of thrust, say from engine defect, would find that by dropping his speed of flight to V_1 he would still be able to keep going; the resistance would here be *less than that for which the machine was designed*. If he were a test pilot he might complain to the designer that some mistake had been made. But the designer with a fuller understanding might reply, "I designed the machine for a flight speed V_2; you are flying it at a flight speed V_1. If you had told me that that was your intention I could have done much better for you, I would have designed the aerofoil for that lower velocity and then the resistance would have been still less." Thus the aerofoil as designed is given in silhouette immediately below the velocity V_2 to which it relates, and then is repeated at the velocity V_1 at which the pilot found the resistance diminished. The observed reduction is indicated at p_2, Fig. 3. The designer if he had designed for the velocity V_1 would have specified a greater wing span, Fig. 4 (lower silhouette), and then the resistance could have undergone a further reduction as indicated by the point p_3. If he had so designed in the first instance the pilot might have made the same observation as before, and then the same argument might have arisen and the whole process repeated.

[17] The words "isospan" or "equispan," which suggest themselves, savour too much of the hybrid.

[18] These which include the tail plane, rudder, etc., present surfaces which are, roughly speaking, proportional to the aerofoil area.

[19] "Aerodynamics," Prop. IV, §165.

[20] "Aerodynamics," Prop. V, §166.

[21] "Aerodynamics," Prop. I, §164.

[22] *Loc. cit. ante.*

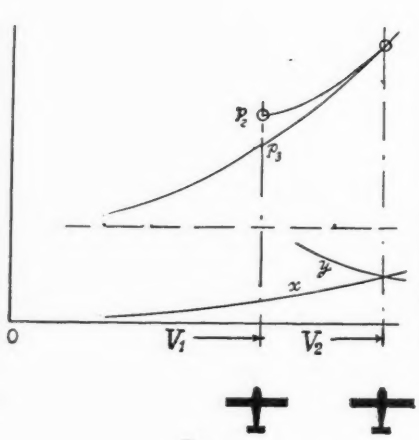


FIG. 3.

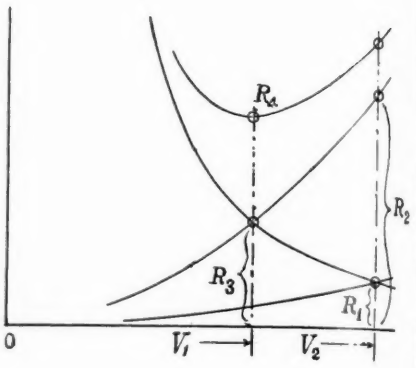


FIG. 5.

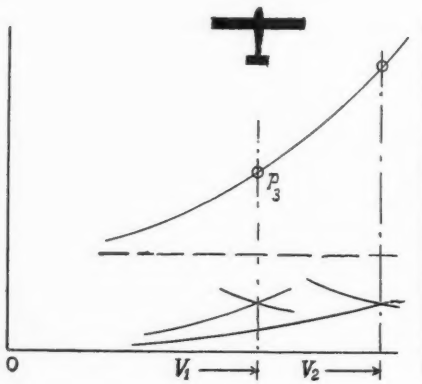


FIG. 4.

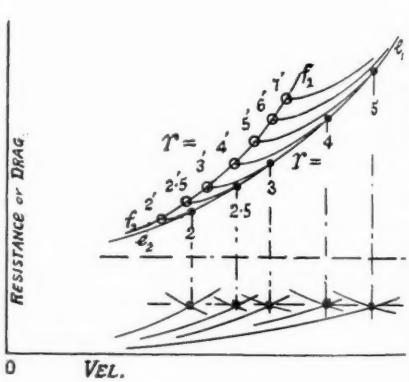


FIG. 6.

§7. RELATIONS: OPTIMUM CONDITION AND LEAST RESISTANCE.

With reference to Fig. 5, R_1 is the direct resistance of the aerofoil without body under optimum conditions; R_2 is the total direct (aerofoil plus body) resistance at optimum velocity $= V_2$. R_3 is the total direct resistance at velocity of least resistance V_1.

Then
$$R_1 V_2^2 = R_3 V_1^2 = \text{const.} = c;$$
$$\text{or } R_1 = c/V_2^2;\ R_3 = c/V_1^2.$$

And
$$\left.\begin{aligned} R_3/V_1^2 &= k_2 = c/V_1^4 \\ R_1/V_2^2 &= k_1 = c/V_2^4 \end{aligned}\right\} k_2/k_1 = V_2^4/V_1^4.$$

Let k_2/k_1 be denoted by r, then $V_2/V_1 = r^{\frac{1}{4}}$. Since r is the ratio of the total direct resistance to the aerofoil direct $(= R_2/R_1)$ the value of V_2/V_1 is determined.

Now take R_3 as unit. Then $R_3 = 2$ and
$$R\ (\text{opt.}) = R_2 + R_1 = (V_2/V_1)^2 + (V_1/V_2)^2 = r^{\frac{1}{2}} + r^{-\frac{1}{2}}$$
$$\text{or } R\ (\text{min.})/R\ (\text{opt.}) = 2/(r^{\frac{1}{2}} + r^{-\frac{1}{2}}).$$

In Fig. 5 as drawn $R_2/R_1 = r = 5$,

$$V_2/V_1 = \sqrt[4]{5} = 1.5$$

$$R \text{ (min.)}/R \text{ (opt.)} = 2/(2.24 + 0.45) = 0.744.$$

§8. Paradox: Further Elucidation.

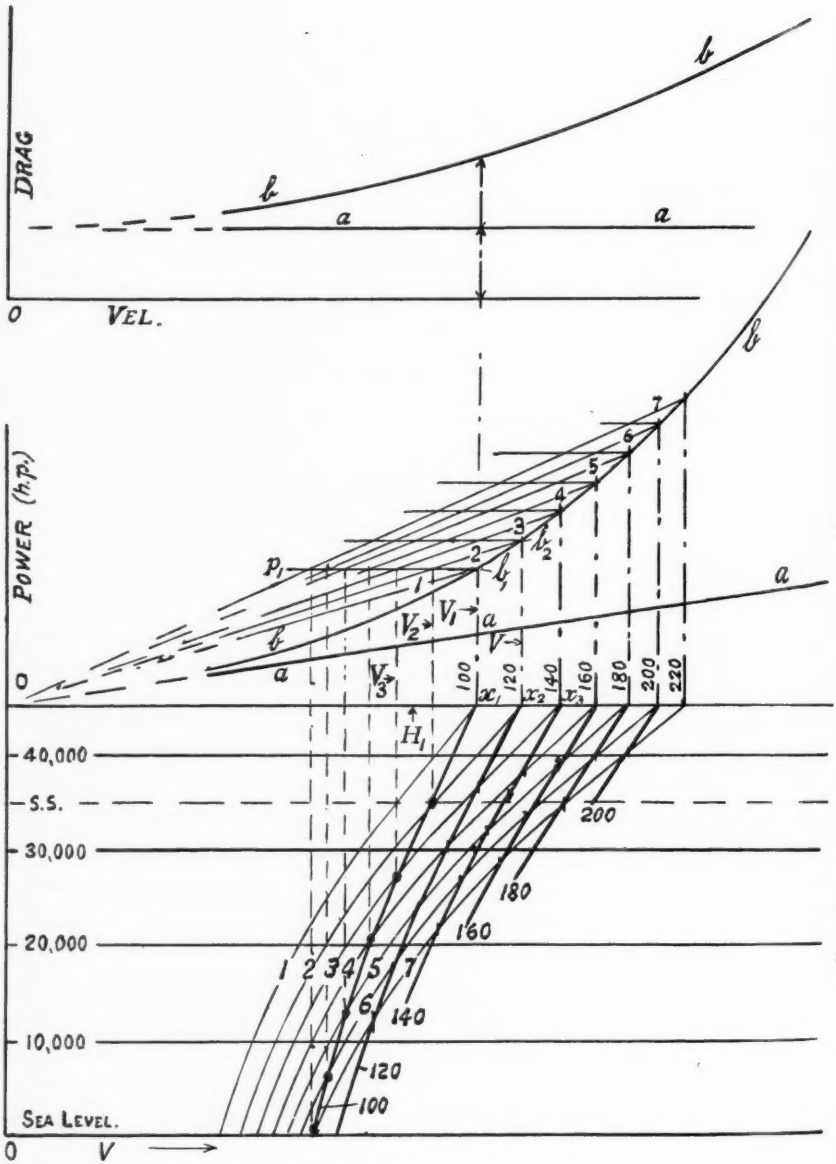
In considering the case of a bodiless glider, the paradox does not arise; also it would not arise if the aerofoil area could be continuously varied whilst in flight to accord with the optimum condition. Thus in Fig. 6, the graph $e_1\ e_2$ represents by its ordinates the total resistance of an aeroplane in terms of velocity (abscissæ) on the understanding that area undergoes continuous variation to comply with optimum condition. The graphs 2′ 2, 3′ 3, 4′ 4, 5′ 5, etc., are plotted on the basis that aeroplanes designed for conditions 2, 3, 4, 5, etc., respectively, are flown at lower velocities to comply with the condition of least resistance (2′, 3′, 4′, 5′, etc.). There is a definite reduction in the resistance in every case. To put this in its true perspective, we may imagine a large number of such graphs to be plotted and a graph $f_1\ f_2$ to be drawn through all the minima, 2′, 3′, 4′, 5′, etc., we are then able to appreciate the true position. An aeroplane flown under the condition of least resistance is always at a disadvantage in comparison with a machine flown at its speed of design (its optimum), inasmuch as the graph 2′, 3′, 4′, etc., lies everywhere above the graph 2, 3, 4, etc. This means that there is no advantage whatever in a reduction of speed, quite the reverse. The apparent gain is a part only of that which could be effected if the machine were *designed* for the lower velocity. It is for this reason that the author defines the *ceiling* as that determined on the basis that the optimum velocity is maintained, that is in accordance with the K-span graphs in Figs 1A, 1B and in Fig. 2, *i.e.*, V varies inversely as $\sqrt{\rho}$. The fact that in the air the pilot of a machine may, by a sacrifice of speed, mount to a very considerable height above the ceiling, as above defined, is of little consequence since the main object of flying high is to exploit the advantage of higher flight velocity.

Speaking generally the velocity of least resistance is of interest to none but the pilot and then only when he is prepared to sacrifice speed.

In the discussion of the author's recent paper more than one speaker was inclined to belittle the importance of the whole theory relating to least resistance, asserting that in practice aeroplanes were flown at much higher speeds than theory would indicate. In the author's opinion this is in part due to a misunderstanding, namely, a lack of appreciation of the real situation—a failure to distinguish between the optimum condition when Prop. IV applies, and the condition of least total resistance when Prop. I holds, that is to say, it is due to a failure to master the technical difficulties which under the title of "paradox" have been dealt with above.

§9. Horse-Power and the K-Power Graph.

It is by now familiar to us that so far as concerns the aerofoil and ancillaries, as represented by a bodiless glider under optimum conditions, resistance is constant in relation to speed provided that the linear parameter S (span) is made to vary inversely as the velocity; also we know the body resistance to be proportional to the square of the velocity; total resistance being the sum of the two; all this relating to the condition of constant density, that is to say, in our atmosphere, the altitude H = constant, as represented in Fig. 7A. When we interpret this in terms of power (horse-power) the graphs require to be multiplied by V. Thus the power expended in overcoming the constant component of the resistance is given by an inclined straight line Oa, Fig. 7B. The power required to overcome the body resistance is represented by a graph of the form P (power) $\propto V^3$; the superposition of these two is given by the graph $b\ b\ b$ (Fig. 7B). It is convenient (Fig. 7A), for reasons which will be given later, to take as a datum the particular velocity at which the body resistance and "bodiless"



Illustrating the derivation of the K-power graph, as related to the optimum condition. Fig. 7a expresses graphically the resistance under optimum conditions as founded on a constant plus body resistance, as relating to some definite altitude. Fig. 7b is the interpretation of this in terms of power (h.p.); with 7c this gives the geometrical construction from which the K-power graphs are derived.

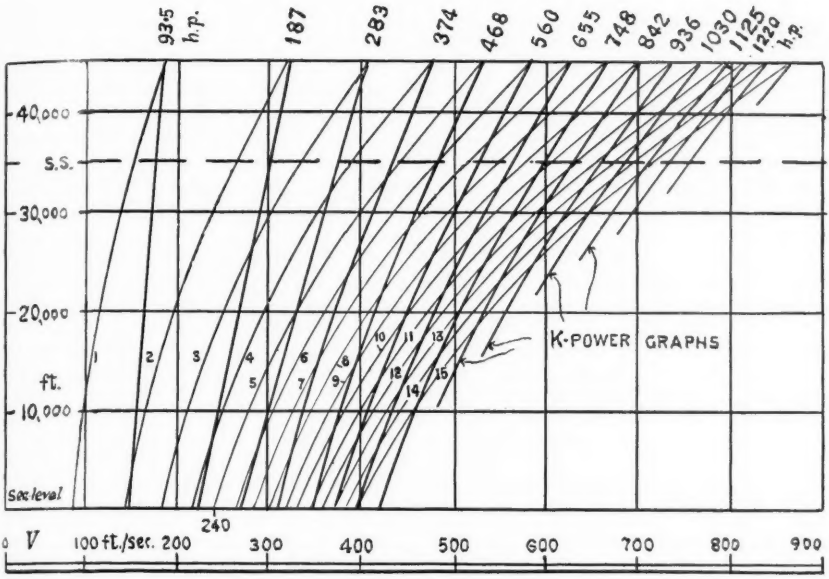


FIG. 8.

In a chart laid out as in Fig. 8 four quantities are represented. The cartesian co-ordinates give H the altitude, and V the flight velocity. The network of graphs define S the span and P the power. So far as concerns the four variables, H, V, S and P, this chart enables us to solve any problem relating to high altitude flying at sight; given any two, the other two are determined. At the ceiling H there is a maximum expenditure of power, consequently, if the power available be known and the desired H be stated, a simple inspection enables us to prescribe the span and the velocity at H and at all lower altitudes. When only one condition is given the aeronautical engineer may make his choice according to his needs. For example, if P (h.p.) only be stated he may compare the advantages of a higher ceiling on a lower K-span graph with a higher K-span graph and lower ceiling. The K-span graph once settled means that he is dealing with a machine "in being." The essential fact is that two of the quantities H, V, S and P must be given in order that the other two shall be determined.

The span in feet corresponding to the numbered K-span graphs for optimum conditions is given in the following Table:—

No. of graph.	Span feet.	
1	145	Velocity too low for useful service.
2	84	
3	66	
4	56	
5	50	Assumed "datum" condition at which body resistance = that of aerofoil and ancillaries.
6	46	
7	43	
8	40	
9	38	
10	36	
11	35	Loading too high for existing aerodrome runways.
12	33.5	
13	32.5	
14	31.6	
15	30.7	

resistance (aerofoil, etc.) are equal, this also applies to the power expended. Thus in Fig. 7B the datum ordinate x_1b_1 is double of the ordinate x_1a. From the point x_1 a K-span graph is drawn which may be continued to sea level, Fig. 7C. Knowing that for this graph the total resistance is constant, the power will vary from point to point directly as the velocity, and therefore a graph representing the power referring to the K-span graph will be a straight line b_1O (directed to the origin O), Fig. 7B, and this will apply in each case to any other K-span graphs. Take, for example, K-span graph x_2 the power required at altitude H will be that given by the ordinate x_2b_2 and the power at lower velocities referred to this K-span graph will be given by ordinates of the line Ob_2.

It will now be apparent that the power required at velocity V_2 on the K-span graph (2) will be the same as that required at velocity V_1 for K-span graph (1) (at H_1 altitude), and so we can describe as a *constant power* or *K-power* graph a line drawn through these two points.

In order to define this K-power line with greater precision, K-span graphs may be plotted for other power values, such, for example, as K-span (3), to which the inclined line correspondingly numbered 3 relate. Where this latter is intersected by the horizontal line b_1p_1 the velocity value is V_3 and a perpendicular let fall on the correspondingly numbered K-span graph (3) gives us a further point through which the K-power graph passes. Similarly, any number of other K-power graphs may be drawn.

§ 10. The Chart.

In Fig. 8, a complete chart is presented laid out in accordance with the procedure given. In this chart altitude H is given in feet. K-span graphs are drawn in their correct relation to altitude $V \propto 1/\sqrt{\rho}$, such that at their "outcrop," velocities correspond to equal increments of power. The K-power graphs are derived from an h.p. graph by the same construction as employed in Fig. 7B. In Fig. 7C the particular condition when the body resistance is equal to the aerofoil resistance is taken as "datum," and the power is expressed as 100 in arbitrary units. In Fig. 8 corresponding power values are given in terms of h.p. as relating to a hypothetical aeroplane of four tons (9,000lbs.) gross weight. The K-power graph marked 468 h.p. is here the *datum* corresponding to the figure 100, arbitrary units, in Fig. 7C.

§ 11. The Chart in its Application.

From this diagram we may deal with any conditions laid down as concerns the machine for which the plotting has been made. Thus suppose that the maximum power available be 500 b.h.p., we may take equivalent as 375 thrust h.p. Then let it be that the service demands a normal ceiling, $H = 30{,}000$ft. the K-power graph cuts the 30,000 level at 415 ft./sec.; this is the optimum flight velocity at the ceiling level prescribed; the optimum sea level velocity of the machine given by K-span graph (between Nos. 5 and 6) will be 250 ft./sec., and the span (from table) = 48 feet.[23] If the aeroplane be flown above the 30,000 level it can only be at a speed below that for which it was designed. The velocity at 30,000ft., namely, 410 ft./sec., is the highest useful velocity for this machine, and as stated should correspond to the engine speed of maximum output; this concerns the effective pitch of the propeller.

The foregoing will, the author believes, serve to illustrate the manner in which the diagram given in Fig. 8 may be laid out to solve any stated problem connected with flying at high altitude.

[23] At 48ft. span the loading will stand at very nearly 40lbs./sq. ft., which may be regarded as inconveniently high, in view of the ground speed which would be necessary before take-off or when alighting. This means that for velocities at sea-level (or other specified level) greater than that in question, the optimum condition may not be capable of realisation: a compromise may be necessary. This would apply to all numbered K-span graphs shown in the chart higher than that in question.

Appendix I.

The Span in Terms of W and ρV^2.

These relations are determined by the following:—

$$W = K_L \text{ (opt.)} \times \rho V^2 \times (S^2/n)$$

in which the last term gives the area in terms of the span S and aspect ratio n, and in which $K_L = 2\sqrt{\mathbf{C}_o n}$; $\mathbf{C}_o$ being augmented 25 per cent. to represent frictional drag on ancillary surfaces.

Or,

$$S = \sqrt{\{ Wn/(2\sqrt{\mathbf{C}_o n} \times \rho V^2) \}}.$$

We may write this alternatively,

$$S\rho^{\frac{1}{2}}V = Wn/K_L \text{ (opt.)}$$

which gives prominence to the fact that if ρ = const. $S \propto 1/V$. Also that for K-span graphs $S \propto 1/\rho^{\frac{1}{2}}V$.

Example.—An aeroplane has a gross weight of 4 tons = 9,000lbs., or W = 290,000 pdls. $\mathbf{C}_o$ from graph given in Figs. 1A and 1B = 0.00134. Add 25 per cent. for ancillary surfaces = 0.0017, let n = 10. Then

$$K_L \text{ (opt.)} = 2\sqrt{(0.0017 \times 10)} = 0.26.$$

Then at gound level ρ = 0·077 and V in graph (Fig. 1A) = 200 ft./sec., thus ρV^2 = 3,100.

$$S = \sqrt{\{ (290{,}000 \times 10)/(0.26 \times 3{,}100) \}} = \sqrt{3{,}600} = 60\text{ft.}$$

and this is the span proper to the graph in question for all altitudes.

At any given altitude, where density is constant, the span may be at once assigned as the inverse of the velocity. Thus in the K-span graphs given in Fig. 2, the span is represented graphically to scale to accord with the values of velocity given. In Fig. 2 for an aeroplane whose gross weight is four tons (= 9,000lbs.), the scale to which the span is laid off is indicated by the top aeroplane whose span is given as 120 feet.

Aerofoil Resistance. Quantitative.

Assuming still a gross weight = 9,000lbs. We take the value of K_L (opt.) as previously = 0.26, and the corresponding value,

$$K_D = K_L^2 (a/2A) + 2\mathbf{C}_o.$$

Here

$$a/2A = 1/2n$$

$$K_D = K_L^2/2n + 2\mathbf{C}_o = 0.067/20 = 0.0033 + 0.0034$$

$$\text{or } K_D \text{ total} = 0.0067$$

$$\text{or } K_D/K_L = 0.0067/0.26 = 0.0257$$

$$\text{Add}^{24} \text{ 5 per cent. } 0.0013$$

$$0.0270 \text{ corrected value.}$$

$\therefore$ Aerofoil drag (+ ancillaries) = 0.027 × 9,000 = 243 pounds.[25]

This, under optimum conditions, is independent of V and ρ.

Body Resistance. Quantitative.

Now we have to imagine a body of some kind and make a computation of its resistance R_b. We will assume:—

[24] In the data tabulated and plotted in Part IV of the author's recent paper, *loc. cit. ante*, it transpired that there is a loss of efficiency equivalent to about 5 per cent. in the case of an aerofoil selected as the best of those to which the records relate.

[25] Or, 7,850 poundals. The pound unit of force is here employed, in view of the subsequent calculation of h.p. in which the familiar expression is used.

A streamline body 25ft. maximum circumference and 40ft. length; "wetted" surface = 720 sq. ft., $C = 0.0012$, $R_b = 0.0012 \times 720 \times \rho V^2 = 0.864\ \rho V^2$ pdls. $= 0.027\ \rho V^2$ pounds.

The most carefully designed body presents a resistance far higher than that of a perfect streamline form. The actual figure is commonly derived experimentally, but for the present purpose it will be taken as twice that calculated on the basis of skin-friction. Thus

$$R_b = 0.054\ \rho V^2 \text{ pounds}$$

This is constant for any K-span graph.

Let R_{af} stand for aerofoil (constant) resistance. Then (datum condition) $R_b = R_{af}$

$$0.054\ \rho V^2 = 243$$

$$\rho V^2 = 243/0.054 = 4{,}500 \text{ or } \rho^{\frac{1}{2}} V = 67.$$

At sea level $\rho^{\frac{1}{2}} = 0.28$, or, $V = 67/0.28 = 240$ ft./sec.

Since $\rho^{\frac{1}{2}} V$ is constant this datum condition relates to the whole K-span graph which, at sea level, corresponds to $V = 240$, see Fig. 8.

The Power Expenditure.

In Fig. 8 we have K-span No. 5 whose ground value is $V = 240$ carried up to 45,000ft. altitude where $V = 530$. At that level the power expended on account of R_{af} will be $(243 \times 530)/550 = 230$ h.p. And, on account of R_b, a like amount (datum condition), total 468 h.p., and in Fig. 8 the K-power graphs are given in terms of h.p. accordingly.

ABSTRACTS AND NOTICES

FROM THE

SCIENTIFIC AND TECHNICAL PRESS.

Issued by the

Directorates of Scientific Research and Technical Development, Air Ministry.

(Prepared by R.T.P.)

No. 42. April, 1937.

Pressure Losses for Fluid Flow in Curved Pipes. (G. H. Keulegan and K. H. Beij, Bur. Stan. J. Res., Vol. 18, No. 1, Jan., 1937, pp. 89-114.) (42/1 4909 U.S.A.)

This paper presents the results of a study of the flow of water in smooth-walled large radius curved pipes for the viscous and turbulent régimes over a range of Reynolds numbers from 500 to 60,000. The discussion is based on data obtained with $\frac{3}{8}$-inch brass tubing. Two series of tests were made. In the first series pressure losses were measured on ten bends, and simultaneous measurements were made on the downstream portion of the straight pipe. In the second series pressure losses were measured on four equal segments on each of four bends. Critical numbers for bends of different curvature ratios when the entering flow is laminar are briefly discussed. Average values for the relative increase in resistance in a bend as compared with straight pipe in the régime of turbulent flow are given for the range of Reynolds numbers from 40,000 to 60,000. The results show that the relative increase in resistance is approximately proportional to the curvature ratio.

On the Relative Motion of a Solid in a Viscous Fluid. (V. Valcovici, Comp. Rend., Vol. 203, No. 21, 23/11/36, pp. 1054-1056.) (42/2 5300 France.)

The author demonstrates the following theorem. The system of hydrodynamic forces acting on a solid moving in a viscous fluid (which is at rest at infinity) augmented by the inertia forces of the displaced fluid is equivalent to the system of forces which the same fluid would exert on the body, if the whole material system (body and fluid) moved so as to bring the body to rest.

Tank Tests of Two Models of Flying Boat Hulls to Determine the Effect of Ventilating the Step. (J. R. Dawson, N.A.C.A. Tech. Note, No. 594, Feb., 1937.) (42/3 5308 U.S.A.)

The results of tests made in the N.A.C.A. tank on two models of flying boat hulls to determine the effect of ventilating the step are given graphically. The step of N.A.C.A. model 11-C was ventilated in several different ways and it was found that the resistance of the normal form is not appreciably affected by artificial ventilation in any of the forms tried. Further tests were made with the

depth of the step of model 11-C reduced and likewise show no appreciable effect on the resistance from ventilation of the step. Tests were made on a model of the hull of the Navy P3M-1 flying boat hull both with and without ventilation of the step. It was found that the discontinuity which is obtained in the resistance curves of this model is eliminated by ventilating the step.

The Thermal Scale of Turbulence (English Text). (L. Witzianski and B. Schwab, Technical Physics, U.S.S.R., Vol. 2, No. 5, 1935, pp. 414-430.) (42/4 5341 U.S.S.R.)

Following the work of Knethe and Dryden, the turbulence in an airstream can be estimated by the value of the Reynolds number for which the resistance coefficient of a sphere becomes equal to 0.3.

It has since been found, however, that the results also depend on the absolute diameter of the sphere and this renders the method rather inconvenient. For this reason, one of the authors suggested as far back as 1931 an alternative method of estimating turbulence depending on the change of the heat transfer coefficient of a sphere immersed in the turbulent air. The procedure when using a thermal scale of turbulence is simple and more exact than the resistance method which depends on taking measurements in a critical stage of flow, when the latter is necessarily unstable and responsive to small influences.

It is possible to use relatively small spheres (7 cm. diameter) and the work is at present being extended to other shapes (streamline, etc.) with a view to investigating their suitability for similar measurements.

A New Stream Function for the Investigation of Rotational Gaseous Motion. (L. Crocco, Z.A.M.M., Vol. 17, No. 1, Feb., 1937, pp. 1-7.) (42/5 5364 Italy.)

The usual methods for the investigation of the motion of gases break down when the velocity of sound is exceeded. In this case, surfaces of discontinuity may form which are associated with changes in entropy, the motion now being no longer irrotational. The usual potential and stream functions now being no longer available, the author proposes a new type of stream function which is defined solely by velocity components. This new function is applicable to the equation of motions of general two-dimensional flow and to those special cases of three-dimensional flow which possess axial symmetry.

The Instability of the Boundary Layer in a Slightly Divergent Channel. (G. Rosenbrook, Z.A.M.M., Vol. 17, No. 1, Feb., 1937, pp. 8-24.) (42/6 5381 Germany.)

The velocity distribution in a divergent channel was obtained experimentally for the two-dimensional case. The method consisted in towing a pair of parallel divergent plates through stationary water sprinkled with metallic powder, the camera moving with the plate. The resultant velocity profile was approximately expressed by a polynomial of the sixth degree and the disturbance differential equation established following the methods of Tollmien (see Translation No. 244) from which it follows that the wave velocity of the neutral disturbance is equal to the fundamental velocity at the point of inflexion of the velocity profile. The author also attempted to determine the critical Reynolds number by means of the equation of dissipation. The attempt failed on account of the approximations introduced when solving the disturbance equations becoming untenable for the relatively small Reynolds numbers in question.

The Effect of a Periodic Source in Water with a Free Surface. (H. Holstein, Z.A.M.M., Vol. 17, No. 1, Feb., 1937, pp. 38-47.) (42/7 5382 Germany.)

The author considers the form of free surface as a function of the strength and period of the source and its distance below the surface in the two-dimensional case

of an incompressible fluid (irrotational motion). At a finite distance from the source, the main constitution of the solution is a complex experimental integral which is solved approximately in series form.

Centrifugal Pumps and Blowers. (British Patent No. 460,489.) (Messrs. Escher Wyss, Switzerland.) (Engineer, Vol. 163, No. 4238, 2/4/37, p. 406.) (42/8 5399 Great Britain.)

It is claimed that in this design of centrifugal multi-stage pump the losses in the passages from one stage to another are materially reduced. The diffusor chambers are so proportioned that their cross-section decreases by at least 10 per cent. in the direction of the flow, so as to increase the velocity and check turbulence. The passages are then provided with streamlined vanes to guide the fluid into the next stage. It is stipulated that the distance apart of the vanes should not be greater than the radial depth of the shortest vane.

A Study of the Factors Affecting the Range of Aeroplanes. (D. Biermann, N.A.C.A. Tech. Note No. 592, Feb., 1937.) (42/9 4925 U.S.A.)

A study has been made of the most important factors affecting the range of aeroplanes. In the first of three parts of the paper the various factors are individually analysed and evaluated relative to each other in order to establish a basis for compromise in design. In the second part the effect of varying a number of the most important factors is determined for a sample aeroplane. In the third part the problem of take-off is investigated for the most critical design conditions encountered in Part II and means for improving the take-off are analysed. The following general conclusions are drawn:—(1) Reduction in overall weight may be of more importance than aerodynamic cleanness. (2) Flight at constant speed or constant power is preferable to flight at constant L/D. (3) A large gain in speed with but little loss in range can be obtained by supercharging the engine to high altitudes. (4) For a given geometric size the gross weight should be the limit fixed by the take-off conditions. (5) Variable pitch props and flaps are of importance in making possible take-offs with greater loads.

The Effect of Lateral Controls in Producing Motion of an Aeroplane as Computed from Wind Tunnel Data. (F. E. Weick and R. T. Jones, N.A.C.A. Report No. 570, 1936.) (42/10 4926 U.S.A.)

Lateral control at low speed and high angles of attack not only depends on the rolling moment introduced but also on secondary forces due to yawing moments introduced by the controls and their effect on the damping in rolling, the other lateral stability derivatives and the moments of inertia of the aircraft. The present report deals with computations which take these additional factors into account and the agreement of the calculation with results of flight tests shows the utility of the method. It appears that for satisfactory control at high angles of attack the damping in both rolling and yawing must be maintained above a definite minimum to avoid an uncontrollable form of instability arising from the interaction of these motions.

The Rolling Friction on Several Airplane Wheels and Tyres and the Effect of Rolling Friction on the Take-off. (J. W. Wetmore, N.A.C.A. Report No. 583, 1937.) (42/11 5231 U.S.A.)

The rolling coefficient of friction varied between 0.009 to 0.077 depending mainly on the type of ground surface, although the type of tyre (high pressure, low pressure and extra low pressure) and the wheel bearing (plain or roller) have also some effect. Speaking generally, the standard type of wheel with high pressure tyres gave the lowest friction. In rough calculation of take-off performance only the type of ground need be considered.

Dollar Values in Airplane Design. (K. Perkins, J. Aer. Sci., Vol. 4, No. 4, Feb., 1937, pp. 139-148.) (42/12 5243 U.S.A.)

This paper explains the application of a partially rationalised method of reaching decisions relating to the general and detail design of an airplane. The method consists basically of assigning, by means which are explained and illustrated, dollar values to differences of weight, differences of speed, etc., which influence design, in order that all such factors may be reduced to common terms. It is shown how this method permits relatively accurate determination of ideal characteristics needed to meet given requirements, and an example is given showing how a typical design problem, involving the determination of the ideal wing span, may be solved.

Muscular Help to Gliding Flights. (Flugsport, Vol. 29, No. 6, 17/3/37, pp. 152-155.) (42/13 5281 Germany.)

From the known performance of a series of high performance gliders, it is estimated that the rate of descent can be halved by the muscular action of the arms and legs of the pilot. The corresponding increase in range will depend on the distribution and magnitude of the vertical air currents. Muscular effort may thus be of use in enabling a pilot to make use of vertical currents which, normally, he would have been unable to reach. Without the help of such currents, none of the existing gliders can be maintained in the air by muscular effort alone.

A Study of the Two-Control Operation of an Aeroplane. (R. T. Jones, N.A.C.A. Report No. 579, 1936.) (42/14 5311 U.S.A.)

The two-control operation of a conventional aeroplane is treated by means of the theory of disturbed motions. The consequences of this method of control are studied with regard to the stability of the aeroplane in its unconstrained components of motion and the movements set up during turn manœuvres. It is found that the motion of a conventional aeroplane is more stable when an arbitrary kinematic constraint is imposed in banking than when such constraint is imposed in yawing. Different means of two-control operation are also discussed and it is concluded that a reliable rolling moment control that does not give the usual adverse secondary yawing moment should be most satisfactory. Several special modifications intended to make the aeroplanes more suitable for two-control operation are also discussed, and it is found that relatively great weathercock stability (N_v) would be desirable.

Carburation for Long Range Flying. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 471.) (42/15 5330 U.S.A.)

For long range work it is essential that the rate of fuel consumption of the engine be regulated within narrow limits. Moreover, it is advisable to maintain either constant air speed or determine a compromise of increased air speed and decreased power. This necessitates control of engine r.p.m. (variable pitch propeller) and induction pressure (boost regulator) as well as mixture strength. The Wright Aeronautical Corporation have designed an automatic carburettor in which the float mechanism is replaced by a diaphragm. This provides automatic compensation to within 10-15 per cent. at altitudes up to 15,000 feet. Ice formation in the carburettor caused by fuel evaporation has been eliminated by providing a clear path for the mixture (no throttle obstruction).

Wibault 25 Tons Civil Aircraft. (Les Ailes, No. 824, 1/4/37, p. 7.) (42/16 5434 France.)

A scale model of this machine fitted with four 20 b.h.p. engines is nearly completed at Villacoublay and will be tested in the full-scale tunnel at Chalais

Meudon. The model will fly under its own power in the tunnel and it is claimed that this method of experimentation has, so far, not been carried out in any other country.

Giant Hydroplane. (Les Ailes, No. 824, 1/4/37, p. 7.) (42/17 5436 U.S.S.R.)

A twin-float gliding boat intended for passenger work on the Black Sea is under construction. It is propelled by four engines (total b.h.p. 2,700) driving airscrews and two auxiliary engines operate water screws for manœuvring in harbours. The machine can carry 150 passengers and a maximum surface speed of 60 m.p.h. is aimed at.

Pre-Chamber Compression Ignition Engine Performance. (C. S. Moore and J. H. Collins, N.A.C.A. Report No. 577, 1937.) (42/18 5310 U.S.A.)

Results of the investigation indicate that for maximum performance of this 5- by 7-inch single cylinder engine at speeds up to 1,500 r.p.m. the compression ratio should be between 15.5 and 17.5 and the pre-chamber should be as large as possible, disc-shaped and connected to the cylinder by a single passage. A strong rotational air flow should be created in the pre-chamber by introducing the passage tangentially. Flaring should be employed on the cylinder end of the passage to spread the issuing gases over the flat piston crown. The fuel spray should be directed across the disc chamber toward the mouth of the connecting passage. Boosting the inlet air pressure effectively raises the power output. As the pre-chamber is inaccessible for scavenging and the lack of clearance under the valves prohibits the use of proper valve timing, the pre-chamber type of cylinder head is judged to be incapable of developing the high specific output required of aircraft engines.

Viscosity Type Oil Cooler, Designed by U.S. Air Corps. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 466.) (42/19 5325 U.S.A.)

A viscosity control valve is illustrated which is directly secured to the cooler and requires no external "plumbing." The operation of the valve is controlled by the pressure in a set of bellows, which in turn is controlled by the throat pressure of a small venturi which by-passes a very small quantity of oil from the inlet to the low pressure side of the relief valve. In order to facilitate engine starting in cold weather, the U.S.A. Air Corps have been experimenting with an oil dilution system, in which the viscosity of the engine oil is reduced by petrol admixture prior to shutting down. The admixture is restricted to the oil in circulation in the engine and the main oil is not affected. Details of the circuit are given.

Aircraft Engine Ratings—Design of Metal Fins. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 468.) (42/20 5326 U.S.A.)

From tests on a single cylinder the following conclusions are drawn:—(1) A considerable improvement in the heat transfer of conventional aluminium fin designs is possible by correctly proportioning the fin dimensions. (2) The optimum thickness of fin decreases as the thermal conductivity of the material increases. (3) Correctly proportioned aluminium fins will transfer more than 2¼ times as much heat as steel fins for the same weight and pressure drop. (4) The best fin proportions for maximum heat transfer for a given pressure drop also give a high heat transfer for a given power expenditure.

French Engine Design. (Autom. Ind., Vol. 76, No. 12, 20/3/37, pp. 470-471.) (42/21 5328 France.)

The following tendencies are noted:—*Under* 30 *b.h.p.*—high speed air-cooled two-stroke (geared). 70-100 *b.p.h.*—radial air-cooled. 100-250 *b.h.p.*—in-line four- or six-cylinder ungeared (air-cooled). 300-500 *b.h.p.*—in-line six-cylinder

ungeared (air-cooled), 12-cylinder V geared (air-cooled). 600-1,000 *b.h.p.*—12-cylinder water-cooled predominate. 1,000-1,600 *b.h.p.*—air-cooled two-row radial largely predominates. On fighting aircraft, spur reduction gear is in favour, since it facilitates the use of the automatic cannon firing through the propeller shaft. Recent experience in Spain has shown that the ordinary machine gun is practically useless against high speed aircraft. The cannon, on the other hand, cannot be easily synchronised to fire through the propeller.

Flexible Valve Seats. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 471.) (42/22 5329 U.S.A.)

The insert material for the valve seat is austenitic nickel chrome valve steel in the form of a ring of inverted U section. The outer member of the ring is sprung into the cylinder wall, whilst the stellited edge of the inner member forms the valve seat. It is stated that this modification enabled continuous runs under detonating conditions to be carried out on a Cyclone (6¼in. bore) which had previously given trouble due to valve seat distortion.

Reduction Gears for Aircraft Engines. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 476.) (42/23 5332 U.S.A.)

In single reduction gears of the spur type, herring-bone gears are now general. Reduction gears of the interplanetary type require careful design so as to equalise the loads on the subsidiary members. At the present time 1,000 b.h.p. engines can be run ungeared (1,000-1,500 r.p.m.). Engines of higher output will have to operate at higher r.p.m. (up to 3,000 r.p.m.). In this case a double reduction gear (ratio 3.5 or 3 to 1) will be required which will be of the spur wheel type.

Factors Influencing the Wear of Valve Seats in Internal Combustion Engines. (C. G. Williams, Engineering, Vol. 143, No. 3715, 26/3/37, pp. 357-358.) (42/24 5335 Great Britain.)

The experiments were carried out on a special machine, in which the exhaust valve could be subjected to the combustion product of a gas flame. Besides varying the nature of the products (oxidising or reducing) the effect of tappet clearance and spring closing pressure were investigated. It appears that wear only becomes appreciable if the valve and seat temperatures exceed a certain limit (approximately 600°C. and 240°C. respectively). Above this temperature, the wear increases rapidly in an oxidising flame, but only slowly in a reducing flame. As was to be expected, at constant speed, the wear is roughly proportional to the spring pressure and the square of the tappet clearance. (To be continued.)

Piston Ring Grooves. (British Patent No. 460,420.) (Engineer, Vol. 163, No. 4237, 26/3/37, p. 377.) (42/25 5339 Great Britain.)

This patent taken out by the Brandenburg Motor Works, Berlin, aims at overcoming wear of ring grooves in light alloy pistons by lining the top groove with a fixed channel-shaped ring in which the normal piston ring operates. Several alternative designs are illustrated.

Fuel Injection Pump. (British Patent No. 461,521.) (Scintilla, Ltd., Switzerland.) (Engineer, Vol. 163, No. 4238, 2/4/37, p. 405.) (42/26 5398 Great Britain.)

This pump is equipped with an accumulator piston acting in opposition to a spring. The downward stroke of the accumulator piston, and consequently the capacity of the pump barrel, can be regulated by a wedge controlled by the governor. The discharge of the oil takes place through a port in the piston, which terminates in a tangential gash. The piston can be rotated by a rack and

pinion gear. In this way the edge of the gash can be used to throttle the discharge and the fuel will be injected into the cylinder at comparatively low loads by the nozzle in a series of puffs, none of which is sufficient to cool the compressed air in the cylinder seriously. When the engine warms up the throttling action is reduced and continuous injection takes place.

Motor Spirit—Total Consumption and Home Production in Great Britain. (Fuel, Vol. 16, No. 3, March, 1937, p. 63.) (42/27 4938 Great Britain.)

The yearly imports of motor spirit in Great Britain amount to approximately $1{,}200 \times 10^6$ gallons, the yearly increase being of the order of 40×10^6 gallons. The hydrogenation plant at Billingham produced 34×10^6 gallons, or less than 3 per cent. of the total requirements. Assuming a possible production of 350 gallons per ton of treated coal, the total requirements of Great Britain could be met by treating 3.5×10^6 tons of coal. Ancillary operations would consume approximately 11.5×10^6 tons, so that out of a total annual coal production of approximately 230×10^6 tons, approximately 7 per cent. would have to be set apart to make Great Britain self-supporting.

Composition for Preventing Vapour Lock in Internal Combustion Engines. (J. E. Essick, Chem. Absts., Vol. 31, No. 5, 10/3/37, p. 1590.) (U.S. Patent No. 2,067,384.) (42/28 5278 U.S.A.)

A composition, to be added in small amounts to hydrocarbon fuel for internal combustion engines to eliminate vapour lock conditions, is formed by mixing kerosene 27¼ gal., nitrobenzene 5½ gal., oil of creosote 10¾ gal., turpentine 2¼ gal., oil of cedar wood 2¼ gal., and camphorated oil 1½ gal.

Anti-Knock Motor Fuel. (I. G. Farb, A.G., Chem. Absts., Vol. 31, No. 5, 10/3/37, p. 1603.) (U.S. Patent No. 2,067,331.) (B.P. No. 459,270.) (42/29 5279 U.S.A.)

Et_4Pb is used as an anti-knock agent together with a small amount of a water soluble (alkali) fluoride such as NH_4F to stabilise the Et_4Pb against light and water. A small proportion of methyl alcohol may be added.

Recent Research Work in Lubrication. (G. B. Karelitz, J. App. Mech., Vol. 4, No. 1, March, 1937, pp. A.31-A.32.) (42/30 5297 U.S.A.)

The work is reviewed under the following headings:—(1) Hydrodynamic theory. (2) Viscosity. (3) Boundary lubrication. (4) Bearing design (including piston rings).

(1) In the case of fluid friction, theory and experiment are in satisfactory agreement. (2) In certain cases the absolute viscosity and the slope of the viscosity temperature curve throw light on the constitution of the lubricant. There is a tendency to replace the commercial type of viscometers (which only give relative values) with instruments of a different type which give absolute readings. (3) Stability film strength, capillary attraction and oiliness all become of importance as soon as the film becomes so thin that the hydrodynamic laws of fluid motion no longer apply. The use of hypoid gears in motor cars has given added importance to this subject and had led to the development of extreme pressure lubricants. Apart from special methods of testing (Timken machine, Adheroscope, etc.), X-ray research has been carried out on the molecular orientation of thin films with a view to determining the effect of various oil admixtures. (4) A considerable amount of work has been carried out on the fatigue of bearing metals (tin base, lead base, bronze, etc.). A new cadmium silver alloy has been investigated. In the I.C. engine, the lubrication of the piston and rings becomes

increasingly difficult as loads increase (supercharging). As shown by several investigations, the increase of friction due to gas pressure may become appreciable. An extensive bibliography (31 items) covering recent work (1935-1936) adds considerable value to the review.

Value of High Octane Number Fuels. (Autom. Ind., Vol. 76, No. 12, 20/3/37, pp. 475-476.) (42/31 5331 U.S.A.)

(1) The revenue earning power of one gallon of petrol is increased from 2 to 5 cents per octane number improvement (for same calorific value). (2) High octane number fuels are of special importance in long range flights. (3) Within practical limits increase in cost of fuel cannot influence trend towards higher octane numbers.

Pressure Drop in Tubing in Aircraft Instrument Installations. (W. A. Wildhack, N.A.C.A. Tech. Note No. 593, Feb., 1937.) (42/32 5232 U.S.A.)

The theoretical basis for the calculation of the pressure drop in tubing is reviewed briefly. The effect of pressure drop in connecting tubing upon the operation and indication of aircraft instruments is discussed. Approximate equations are developed, and charts and tables based upon them are presented for use in designing installations of altimeters, air speed indicators, rate of climb indicators, and air-driven gyroscopic instruments.

The Duration of Spark Discharges Through a Gas Tube. (M. Laporte, Comp. Rend., Vol. 201, No. 23, 2/12/35, p. 1108.) (42/33 5318 France.)

A rotating mirror device is described, the image of the spark being registered on a stationary photographic plate. The speed of rotation is measured in a simple manner by combining the mirror with a siren, the pitch of the sound being measured by means of a tuning fork. The gas tube contained a mixture of argon and mercury vapour at a pressure of approximately 1 mm., and the duration of the spark was of the order of 10^{-5} seconds.

New Instrument for Recording Vibration in Flight. (Autom. Ind., Vol. 76, No. 12, 20/3/37, p. 469.) (42/34 5327 U.S.A.)

The vibrations are recorded electrically, a number of pick-up units operating a single central amplifying and recording unit. Each pick-up is specially adapted to the type of vibration it is intended to measure and is so small that it does not affect the vibration characteristic of the member to which it is attached. By recording the relative motion of two points, the vibration recorder can give information as to the straining of a particular part. An interesting application of the strain pick-up is the recording of engine detonation. For this purpose the gauge is connected between a cylinder stud and the spark plug shell, the detonation producing an electrical output which can be measured on a long period galvanometer.

Anodic Coating of Magnesium Alloys. (R. W. Buzzard and J. H. Wilson, Bur. Stan. J. Res., Vol. 18, No. 1, Jan., 1937, pp. 83-87.) (42/35 4908 U.S.A.)

Magnesium alloys may be anodised in a bath of sodium phosphate and sodium dichromate. The film obtained combines both corrosion-resistance and paint-holding properties, without serious change of dimensions of the treated piece, even on machined surfaces. (Eleven references.)

Aircraft Materials in the U.S.S.R. (Metals). (L'Aerophite, Vol. 45, No. 2, Feb., 1937, p. 38. See also Vol. 44, No. 12, Dec., 1936, pp. 278-280.) (42/36 4944 U.S.S.R.)

In the manufacture of special steels, there is a growing tendency to replace Ni and Tungsten, wherever possible, by Vanadium, Chromium or Cobalt. This

tendency is probably mainly governed by economic reasons which also account for the intense research into bearing metals free from tin. In the production of copper and aluminium, U.S.S.R. hopes to become self-supporting in the near future. The use of Titanium (a native product) in aluminium alloys is stated to have given good results.

Experimental Studies of the Effective Width of Buckled Sheets. (R. Lahde and H. Wagner, L.F.F., Vol. 13, No. 7, 20/7/36. N.A.C.A. Tech Memo. No. 814, Dec., 1936.) (42/37 2637 5062 Germany.)

Aeroplane design makes frequent use of thin sheet metal or plywood shells which buckle under shear and compression stresses, although some support is given at the point where sheet and angles join. So far as it deals with the absorption of compressive stresses this fact is allowed for in the calculation by introducing a participating stress bearing or "effective width," *i.e.*, a part of the sheet section of certain width is allocated to the section of the edge stiffener. The object of the present experiments is a more exact determination of the effective width for the case of pure compression and of the sheet clamped at the angle section. From the experimental data on the effective width the calculation of the buckling load of an angle joined to a thin sheet is then deduced. The experimental results for simultaneous appearance of transverse forces in the buckled sheet (tension fields) are reserved for a continuation of this article in a subsequent issue.

Thermal Stress. (J. N. Goodier, J. App. Mech., Vol. 4, No. 1, March, 1937, pp. A.33-A.36.) (42/38 5298 U.S.A.)

The paper gives a list of formulæ for the thermal stress arising in a number of fundamental cases (rods, plates and tubes). In all cases when the thermal stress is appreciable but still within the elastic limit, the expression for its value is of the form $KE\alpha T$ where E = Young's modulus, α = coefficient of expansion, T = temperature difference measured in a way depending on the particular problem, K = a numerical factor ranging from 0.5 to 2.5. Holes, flaws, notches, and other source of stress concentration are not considered in the article. Taking $E\alpha T$ as representing the order of magnitude of the thermal stress, we obtain a value of 200 lb./sq. in. per degree F. for steel. The yield point is thus reached for this material when temperature differences of the order of 200°F. exist within the material. If the material is mechanically loaded in addition, much smaller internal temperature differences may have to be considered.

Increasing the Fatigue Strength of Press-Fitted Axle Assemblies by Surface Rolling. (O. J. Horger and J. L. Maulbetsch, discussion of paper, J. App. Mech., Vol. 4, No. 1, March, 1937, pp. A.37-A.39.) (42/39 5301 U.S.A.)

According to Föppl, engineering metals are heterogeneous, the constituent crystals being arranged at random and exhibiting very different amounts of cohesion. The stress distribution under load is thus far from uniform and the maximum stress may exceed the average stress ten or even a hundred times. The first breakdown of the material will then occur in small isolated regions and provided the load keeps within certain limits, the damage will not spread. The preliminary loading may even be considered as strengthening the material, since the stressing becomes more equalised. These remarks, however, only apply if the regions of breakdown are surrounded by sound material. If situated near the free surface of the metal, stress equalisation is rendered more difficult and the presence of any flaws in the surface becomes of great importance. Unless special precautions are taken, machined surfaces generally show microscopic cracks, but by subjecting the surface to mechanical treatment (rolling, etc.) the small fissures can be eliminated and the fatigue strength very considerably increased.

A New Alloy of High Density. (C. J. Smithells, Nature, Vol. 139, No. 3516, 20/3/37, pp. 490-491.) (42/40 5314 Great Britain.)

A mixture of 95 per cent. tungsten and 5 per cent. copper powders is heated to 1,450°C. for one hour in a steel die in an atmosphere of hydrogen. The resultant alloy has a density of the order of 17 gm./cc. The alloy is readily machined, using a tungsten carbide tool, and although primarily intended for radium containers, it has been used for balancing crankshafts of racing car engines and similar applications in aircraft engines appear possible.

Chemical Exploration of the Stratosphere. (F. A. Paneth, Nature, No. 3509, 30/1/37, pp. 180-182, and No. 3510, 6/2/37, pp. 220-223.) (42/41 4676, 4932, Great Britain.)

If the stratosphere is free from air currents the constituent gases of the atmosphere should sort themselves out on a density basis. The most suitable gas for testing this appears to be helium and the author has developed a micro method for measuring quantities of a few millionths of a cubic centimetre with an accuracy of 1 per cent. The automatic sounding balloon used at Kew Observatory is described. When the envelope bursts at the ceiling, a previously evacuated glass bulb (500 cc.) is put in communication with the surrounding atmosphere and resealed electrically after 15 seconds whilst the instrument descends by parachute. Altitudes of 23,000 metres have been reached whilst 31,000 m. has been recorded in Germany, using a slightly larger balloon. The *He* content of the atmosphere shows a definite increase at about 18,000 m. (5 per cent. at 23,000 m.). The rate of increase is, however, much less than would be expected if the quiescent atmosphere existed at these altitudes (13 per cent. per km.). There is thus no evidence of a sudden change in condition of the stratosphere at 20 km., the influence of air currents persisting even at this altitude and depending on general weather conditions.

Natural and Artificial Clouds. (D. Brunt, Nature, Vol. 139, No. 3517, 27/3/37, p. 541.) (42/42 5316 Great Britain.)

When an unstable layer of fluid breaks down, the resultant motion is in the form of prismatic cells. In the case of air, the motion of a relatively shallow layer rendered unstable by heating from below consists of a large number of ascending currents surrounded by much slower descending currents. If the heated air is contained in a glass box, motion of the upper plate will produce a variety of phenomena closely resembling cloud phenomena. Typical examples are small cloudlets on a background of blue sky, cloud sheets which show a series of clear holes and clouds in rolls which correspond to the longitudinal or transverse rolls obtained in the model with rapid or slow shearing of the upper plate.

The Albedo of Clouds and the Earth's Surface. (K. Stuchtey and A. Wagener, Nachrichten der Königlichen Gesellschaft der Wissenschaften zu Göttingen, Mathematical Physical Series, 1911, No. 1, pp. 209-235.) (42/43 5406 Germany.)

The experiments were carried out from a balloon, the albedo of the cloud or earth below the balloon being compared with that of a plaster of Paris plate using the Marten's polarisation photometer. Since the construction of the instrument necessary shields the plaster plate from some of the sky light, the value of the cloud or earth albedo has to be reduced in order to obtain a fair comparison. Independent experiments led to a correction of approximately 7 per cent. for this effect. The absolute value of the albedo for the plaster plate was determined subsequently in the laboratory as being equal to unity. Altogether four balloon

flights were carried out and over 200 measurements were taken. The following are average values for the *albedo of clouds*:—

Stratus clouds	600 m.	0.54
,, ,, ...	1,600 m.	0.76
Cumulus clouds	1,600-3,000 m.	0.67

Average values for *albedo of earth's surface*:—

Fields	0.15
Forests	0.06

(Altitude 600-1,600 m.)

Heat Transfer to Fuel Sprays Injected into Heated Gases. (R. F. Selden and R. C. Spencer, N.A.C.A. Report No. 580, 1937.) (42/44 4927 U.S.A.)

A study has been made of the influence of several variables on the pressure decrease accompanying injections of a relatively cool liquid into a heated compressed gas. Indirectly, this pressure decrease and the time rate of change of it are indicative of the total heat transferred as well as of the rate of heat transfer between the gas and the injected liquid. Air, nitrogen, and carbon dioxide were used as ambient gases; Diesel fuel and benzene were the injected liquids. The gas densities and gas fuel ratios covered approximately the range used in compression ignition engines. The gas temperature ranged from 150°C. to 350°C. Several general conclusions may be drawn from the experimental results:— Vaporisation begins immediately after start of injection; the initial rate of heat transfer is a direct function of the initial temperature difference between the gas and the fuel; and the heat transfer is less efficient the greater the injected fuel quantity, even though the total heat transferred is greater.

The Laws of Heat Transmission in a Flowing Medium. (M. Lang, Ann. d. Phys., Vol. 24, No. 5, Nov., 1935, pp. 393/408.) (42/45 5307 Germany.)

If the classical theory of Fourier is applied to the temperature distribution in a hydrodynamic field of flow, heat transfer takes place up to infinity even if the direction is opposed to the velocity of the medium. This is contrary to experience, the optical investigation of the field of flow round a heated tube showing a discontinuity beyond which the temperature field does not extend.

The author attributes this to the fact that heat conduction is a molecular phenomenon, the medium not being continuous as required by the Fourier analysis. Making allowance for this fact, new equations of heat transfer are derived by the author which show that heat transfer cannot take place into a medium if the latter is moving against the temperature gradient at a velocity approximately double the mean molecular velocity.

The Heat Transfer of a Gas Moving at Very High Speeds in a Cylindrical Tube. (German text.) (A. Guchmann and others, Technical Physics, U.S.S.R., Vol. 2, No. 5, 1935, pp. 375-413.) (42/46 5340 U.S.S.R.)

Considerable difficulties arise in the theoretical treatment of heat transfer problems as soon as the velocity of the gas is such that compressibility can no longer be neglected. The authors carried out experiments at air speeds ranging from 100 to 300 m./sec., the temperature of the air entering the tube being approximately 300°C. whilst the tube itself was immersed in boiling water. The pressure of the air at entry was of the order of 3-4 atmospheres, the exit being atmospheric. The heat transfer coefficient α increased over the speed range employed from app. 150 to 400 cal./m.²/h./°C. In calculating the above results, the gas temperatures used are those recorded when the air is brought to rest at

the thermometer. The experiments give the following simple relationship for the Nusselt and Peclet numbers:—

$$Nu = 0.017\ Pe^{0.82}$$

and from this it is concluded that under the condition of the experiments the compressibility phenomena are restricted to comparatively small regions near the exit of the tube.

Ultra High Frequency Wave Propagation over Plane Earth and Fresh Water. (R. C. Colwell and A. W. Friend, Proc. Inst. Rad. Eng., Vol. 25, No. 1, Jan., 1937, pp. 32-37.) (42/47 4895 U.S.A.)

The propagation of 59 to 98 megacycle waves over the plane earth and fresh water was measured and a simple equation for the field strength was developed. Propagation over very deep fresh water was found to be no better than that over plane dry earth.

Directional Antennæ. (G. H. Brown, Proc. Inst. Rad. Eng., Vol. 25, No. 1, January, 1937, pp. 78-145.) (42/48 4898 U.S.A.)

The object of this paper is to develop analytical methods which are readily applicable to the general problems that arise in array design and to provide design curves that may be used without reference to the field theory underlying the problem. The cases of both driven and parasitic arrays have been treated. Where possible, the results have been by comparison with experimental results. In the case of a single parasitic reflector, it is found that spacings less than a quarter wave length are desirable both for transmitting and receiving. It is seen that the parasitic antenna functions equally well as a director or a reflector. The case of an antenna parallel to an infinite sheet acting as a reflector is treated. It is shown that it is desirable to space the antenna very much less than a quarter wave length from the sheet. Other appendices give the derivation of the expressions for the electro-magnetic field in the vicinity of a straight wire, end-loaded, and of arbitrary length, and the extension of these expressions to yield the vertical radiation characteristics at great distances.

Klein Accumulator with Small Self-Discharge. (G. Nehlep and K. H. Koepernik, J. Soc. Chem. Ind (Abstracts B), Vol. 56, February, 1937, p. 149.) (42/49 4952 Germany.)

The cell has a rod anode of PbO_2 surrounded by a cylidrical Cd plate as cathode, in 32 per cent. H_2SO_4 the reactions being $Cd + PbO_2 + 2H_2SO_4 \rightleftharpoons CdSO_4 + PbSO_4 + 2H_2O$, and the e.m.f. 2.24 volts with no load. Charge and discharge curves are given for 100 milliamp. The self-discharge is only 1 per cent. in one month, 2-3 per cent. in two months, and 7 per cent. in three months. The cell is lighter than a Pb accumulator, and is suitable for use in high tension batteries.

Ultra Short Wave Refraction and Diffraction. (T. L. Eckersley, J. Inst. Elec. Eng., Vol. 80, No. 483, March, 1937, pp. 286-304.) (42/50 5215 Great Britain.)

The work of G. N. Watson on the propagation of electric waves over a spherical earth has been extended by the author to take account of the finite resistivity of the earth, the effect of which is of great importance in ultra short wave transmission. The work is in such a form that the field intensities above the earth can be computed numerically. The effect of refraction in the earth's atmosphere can also be taken into account. The results for a range of wave length between 2 and 10 m. and for heights up to 4,000 m. and distances up to

400 km. are published in the paper in a set of curves, the general properties of which are discussed. The effect of atmospheric refraction is considered, and a comparison between observation and theory is made, in which good agreement is obtained, on the average, when neglecting refraction. Major changes may, however, be produced occasionally by refraction.

The Performance of Coil Ignition Systems, with Particular Reference to Double Contact-Breakers and the Effects of Variation of the Period of Open Circuit. (W. R. Debenham, J. Inst. Elec. Eng., Vol. 80, No. 483, March, 1937, pp. 329-341.) (42/51 5216 Great Britain.)

The paper deals with experimental results obtained on a modern coil ignition system operated by a double contact-breaker with a small angle of open circuit. At high speeds the contact-breaker closes before the spark discharge ceases. A theoretical investigation, based on the results, is carried out to determine the approximate increase in sparking frequency with a given output, due to the effect of the persistence of the spark discharge, for various periods of open circuit. Under certain conditions, the estimated increase is 35 per cent. for 0.4 millisecond and 63 per cent for 0.1 millisecond. The maximum sparking frequency of 12-volt coil systems, capable of meeting the output requirements of the service specification for ignition apparatus, is estimated for various values of the open circuit period. It is shown that the probable limit for reliable operation with a double contact-breaker is about 300 sparks per sec. per coil.

REVIEWS.

AIRMAN FRIDAY.

William Courtenay. Hutchinson and Co. Price 12s. 6d.

William Courtenay is well-known in aviation as a brilliant publicity expert. Much of the fame which has come to certain pilots would, despite their often remarkable flights, have died away, a nine days' wonder, if it had not been for the skill of the author in keeping them before the public. How far this is a good or bad thing for those concerned, or for aviation in general, it is not within the competence of the reviewer to express an opinion. But it is certain that from a purely publicity point of view Mr. Courtenay has done his work extremely efficiently and in this book he gives some account of his methods and of the many famous people in aviation with whom he has come in close contact.

The author, himself a fully qualified pilot, went to sea at 15, joined the army at 17, took part in the landing at Suvla Bay, invalided home, returned to the Holy Land to win the Military Medal, returned to Cairo where he became an officer in the Royal Air Force, gaining an experience of sea, land and air which was to prove invaluable.

In the years which followed he helped to organise the tours of Sir Alan Cobham in the famous "Youth of Britain," the reception to Amy Johnson following her amazing solo flight to Australia, and afterwards the outstanding series of flights made by Miss Johnson and James Mollison. In 1932 the author, as an accredited newspaper correspondent, made a flight to India and back with Captain Stack. That year Courtenay met, and helped to make known to the public, Edward Hillman, whose dynamic personality built up a road transport service from nothing, to sell to the London Passenger Transport Board for £145,000 in four years, began Hillman's air services, and died at the early age of 45, a definite loss to air transport.

There are few well-known personalities in aviation the author has not met. He throws a vivid and interesting light on the finance of long distance and stunt flights and their organisation. Airman Friday is, indeed, a book of real live interest to those interested in aviation and is packed with unexpected side-lights from first hand experience. It is a book of reminiscences which can be thoroughly recommended.

THE CONQUEST OF THE STRATOSPHERE.

Chas. E. Philp. Sir Isaac Pitman and Sons, Ltd. 1937. 7s. 6d. net.

There is a rapidly growing literature on the stratosphere, written both from the technical and popular point of view. On the whole there appears in this literature to be an optimism for stratosphere flying in the comparatively near future which is not justified by the known technical difficulties.

This book is almost wholly concerned with stratosphere flights made by balloons, M. Piccard's first stratosphere ascent on May 27th, 1931, to the flight of " Explorer II " on November 11th, 1935. The reports of these flights are given in considerable detail and where scientific records are available they are given. They all go to show the great difficulties which must be overcome before the conquest of the stratosphere becomes a practical reality. As a record of pioneer stratosphere balloon flights the book under review is an excellent and absorbing record, a record which reveals the high courage of those concerned, and the careful technical preparation and scientific study which made many of them so successful.

The scientific data which has been collected will certainly be of use to those who are contemplating stratosphere flights in heavier-than-air craft, though much of the data which is required is, from the very nature of the flights, missing. The data is slowly being collected by high altitude experimental flights now being carried out at Farnborough, in the United States of America, Russia, and Italy. But, in the opinion of the reviewer, unless a new motive power is developed, it is likely to be many years before stratosphere flight, flights at heights of 40,000 feet and over, will become the commercially paying proposition which its enthusiasts believe it ultimately will be.

The 616th Lecture to be read before the Royal Aeronautical Society since its foundation on January 12th, 1866.

PROCEEDINGS.

A meeting of the Society was held in the Lecture Theatre of the Royal Society of Arts, 18, John Street, Adelphi, W.C.2, on Thursday, February 11th, 1937, when a paper on " Aeroplane Stability and the Automatic Pilot " was read by Messrs. F. W. Meredith and P. A. Cooke. In the chair, Mr. H. E. Wimperis, C.B., C.B.E., F.R.Ae.S., President of the Society.

The PRESIDENT: The lecture was on a very difficult subject—at any rate most people who had tried to do any inventive work on these lines had found it difficult—namely, Aeroplane Stability and the Automatic Pilot. The lecture was a joint one by Messrs. Meredith and Cooke, who had arranged between themselves that Mr. Meredith should do the talking. Both were officers in H.M. Service. Mr. Meredith, formerly of Trinity College, Dublin, had been on the research scientific staff of the Air Ministry for many years, and had now the responsible task of being head of the Physics and Instruments Section of the Royal Aircraft Establishment. Mr. Cooke, of University College, London, served in the same kind of work at the Royal Aircraft Establishment, but for the last few years he had been working in the Air Ministry. He knew both authors well, and he could assure the very large audience that, difficult as the subject was, it was tackled in the present paper by those who were particularly competent to do so.

AEROPLANE STABILITY AND THE AUTOMATIC PILOT.

By F. W. MEREDITH, B.A., and P. A. COOKE, O.B.E., M.C.

The authors wish to express their appreciation of the great honour they have been paid in being requested to present a paper to the Royal Aeronautical Society. They would state that, although they have been granted permission by the Air Ministry to present the paper, they alone are responsible for the views expressed.

Automatic pilots are gradually coming into general use all over the world. Their usefulness has now been proved over a period of about ten years in this country and over a somewhat shorter period in other countries, notably the U.S.A., where the Sperry Automatic Pilot has been evolved after many years of pioneering work. Early pioneering work had also been done in this country by Mr. T. W. K. Clarke before the war.

The world's patent literature shows that inventors have been interested in the problem for at least a quarter of a century. Indeed, this was inevitable since the automatic helmsman or " Iron Mike " for marine craft was a proved success and the vagaries of their younger sisters of the air clearly indicated the need for firmer handling in their case also.

Although the common elements of the modern automatic pilot, the gyroscope and the steering engine or servomotor, together with a deviation detector coupled both to the gyroscope and to the servomotor so as to meter the required amount of helm, were already used for marine craft, many inventors have wasted much effort in the search for other and supposedly simpler arrangements.

Some inventors were frightened by the weight of the ship's steering engine and hoped to operate the controls of the aeroplane directly by gyroscopic torque. Had they seen the problem clearly they would have realised that the same gyroscope cannot perform the two functions of exerting relatively heavy torques and defining a required direction.

Other inventors, perhaps after unfortunate experiences with gyroscopes in flight, came to the conclusion that the gyroscope was more wanton than the aeroplane. Of these disillusioned inventors, some said good-bye to the gyroscope and sought for a solution of the problem with pendulums and wind vanes as detectors of disturbances. Others, so to speak, put the gyroscope in a straight jacket by abandoning one of the gimbal-rings and anchoring the remaining one with a spring; in other words, they substituted the restrained gyroscope from the familiar rate-of-turn indicator for the unruly free gyroscope.

Before considering the merits and demerits of the diverse systems which have resulted, it is necessary to get a clear idea of the problem for which a solution is sought. To do so completely would involve an excursion into the mathematical theory of the stability of a mechanically controlled aeroplane, which would be outside the scope of the present paper. It is, however, necessary to survey broadly the concepts with which the mathematical theory deals.

STABILITY (GENERAL).

Some of the following remarks will naturally appear trite to those who are familiar with stability theory. Nevertheless, since there are so many confusions

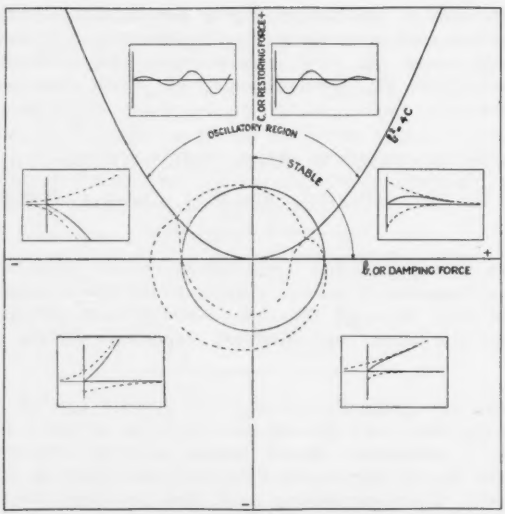


FIG. 1.
DIAGRAM REPRESENTING THE TYPES OF MOTION OF A SYSTEM OF ONE DEGREE OF FREEDOM
EQUATION - $\frac{d^2x}{dt^2} + b\frac{dx}{dt} + cx = 0$

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current, it is desirable to be clear, even at the expense of tediousness, about essentials.

The term stability is often confused with the state of equilibrium. A system is in equilibrium if the forces acting on it are balanced so that it has no tendency to depart in one direction rather than another. For example, the donkey placed midway between two bunches of carrots is—in theory—in equilibrium. So is the donkey placed in contact with one bunch of carrots. The two states of

equilibrium differ, however, in regard to stability in that the donkey between the two bunches of carrots is in a precarious state of equilibrium and having been biased, by any extraneous circumstance, towards either of the bunches, it will become increasingly biased as it departs from its original state of equilibrium. When, however, the donkey has settled down to the job of consuming one of the bunches of carrots, it will be in stable equilibrium, the state in which a system returns to its original state after any small disturbance. (The restriction to small disturbances will be readily appreciated from the example of the donkey, since, if it is taken sufficiently far from the bunch of carrots to come under the greater influence of other attractions, it will not return.)

It will be appreciated that the question of stability does not arise unless the prior condition of equilibrium is already satisfied.

The first function then of any automatic pilot is to put the aeroplane in equilibrium in the required attitude of flight or, in common parlance, in trim. Manual adjustments to achieve the desired trim may, of course, be used.

In general a stable system with one degree of freedom, when disturbed, returns to its state of equilibrium by a decreasing or damped oscillation.

As the proportions and sign of the restoring force and the damping force resisting velocity are varied the motion takes on different characters. The character of the motion is determined by the solution of the equation

$$d^2x/dt^2 + bdx/dt + cx = 0$$

in which x represents the displacement from the equilibrium position;
b represents the damping force or moment; and
c represents the restoring force or moment.

The types of motion represented by the solution of this equation are represented diagrammatically in Fig. 1, in which the vertical ordinate represents the restoring force and the horizontal ordinate the damping force.

Any combination of values of the coefficients b and c is represented by a point on the diagram. If these constants are large the motion is rapid, if small, slow.

The axes and the boundary representing the condition $b^2 = 4c$, divide the field into six regions, each of which represents a different character of the resulting motion. These characters are illustrated by the six insets. Within the parabola, *i.e.*, when b^2 is less than $4c$, the motion is oscillatory.

In the right hand top quadrant, b and c both positive, a disturbance subsides and the motion is said to be stable. For all other conditions the motion is unstable.

A key to the diagram is drawn about the origin. A subsidence is represented by a dotted line inside the full circle and a divergence by a dotted line outside the circle. The relative rapidity of the motion is represented by the distance of the dotted line from the circle in each case. Thus, where the dotted line cuts the circle, as it does when there is no restoring force ($c = 0$), the disturbance will neither subside or diverge, but will persist indefinitely.

The diagram shows that a stable oscillatory system will degenerate to an unstable state of increasing oscillation if the damping coefficient diminishes to the extent of a change of sign and that further increase of the negative coefficient will eventually lead to an aperiodic unstable state in which the motion consists of two relatively rapid divergences.

Moving round the circle in the opposite direction from the normal stable oscillatory state, by decreasing the restoring coefficient c, the motion degenerates into two subsidences of which one gets progressively slower and becomes a divergence when the restoring coefficient changes sign.

It should be noted that a slow divergence is not difficult to control, but a rapid divergence or a divergent oscillation may be difficult to control and extremely dangerous. Also it should be noted that the dangerous régime of double divergent instability will normally be reached by an aggravation of the cause of oscillatory instability—negative damping.

A pendulum in a viscous fluid illustrates the types of stable motion. When the viscosity of the fluid is great an initial velocity of the pendulum will subside rapidly and the bob will return to the vertical by a slow subsidence. The greater the damping, the faster will be the former kinetic subsidence and the slower the latter potential subsidence. It follows that in order to achieve the most rapid recovery from a disturbance, there will be an optimum amount of damping which in fact is slightly less than the damping required to render the motion aperiodic.

The Stability of an Aeroplane.

An aeroplane possesses six degrees of freedom—three translations and three rotations for the three axes. It might therefore be supposed that the general motion of a disturbed stable aeroplane would comprise six simultaneous oscillations of diverse frequencies and diverse degrees of damping or the degenerate form in which pairs of subsidences replace one or more damped oscillations. This condition would be represented mathematically by an equation of the 12th degree with six pairs of complex roots of the form $\alpha \pm i\beta$ in which the constants α define the damping and the constants β define the period of the corresponding oscillation. Four of the roots of this equation are, however, zero in virtue of the fact that the forces and moments on the aeroplane are indifferent to displacements along each of the three axes and to orientation about the vertical axis. Since, however, velocities of translation and of rotation in azimuth do produce forces and moments, one root only is suppressed in respect of each of these four degrees of freedom. Thus the stability equation of an uncontrolled aeroplane is of the 8th degree.

Of the six degrees of freedom three (θ, x, z) involve only motion in the fore and aft vertical plane, the other three (ϕ, ψ, y) for small displacements, involve only lateral disturbances. Hence the motions can be kept separate and the stability can be studied in two independent groups known as Longitudinal Stability and Lateral Stability. Each of these groups contains four of the roots of the original general equation. In the longitudinal group the normal stable aeroplane executes two damped oscillations corresponding to two pairs of complex roots. In the lateral group, however, one pair of roots are generally real, representing two subsidences instead of the more usual damped oscillation. The reason for this will become apparent when the motions are considered in more detail.

Longitudinal Stability.

The degrees of freedom involved are θ, x and z, involving change in pitch, in forward speed and in incidence.

The two modes of oscillation can be seen to be:—

(1) Quickly corrected disturbances involving primarily change of incidence in which changes in forward speed are negligible;

(2) Slow disturbances of forward speed in which change of lift is negligible, or nearly so.

The first is essentially quick since the extra lift due to change of incidence will quickly counter a velocity along the normal axis; thus the incidence will be quickly adjusted until the lift is nearly equal to the weight. Were there no pitching moment with change of incidence, that is, if the weathercock stability in pitch were neutral, the pitching motion which is damped by the tail and the motion along the Z axis which is damped by change of lift would be independent, the motion being two subsidences. Generally, however, there is a pitching moment due to change of incidence which couples the two motions together to produce a well damped short period oscillation.

If, however, there were no pitching moment due to change of incidence, the aeroplane would be in trim at any speed and it would not recover from a deviation in its direction of flight in pitch.

If the aeroplane is stable, there is a pitching moment due to change of incidence which will slightly increase the incidence if the aeroplane is flying at a higher speed than that for which it was trimmed. This causes the second mode of oscillation, which was named by Lanchester the " phugoid." It is necessarily poorly damped, as the damping depends mainly upon the change of drag with speed, and it is generally of a long period since only small changes of incidence are involved and the pitching moment due to incidence change is also generally small. If this pitching moment is of the wrong sign, divergent instability will appear.

It will be clear that the aeroplane designer has no difficulty in regard to the first mode of oscillation, but that the long period oscillation involves necessarily a slow recovery from any disturbance of the flight path. Nearly neutral weathercock stability is desirable to avoid a heavy elevator control and this means that a slight modification of the loading, causing a movement of the centre of mass, may result in failure to recover from a disturbance. Such an aeroplane requires constant attention to the elevator control.

An aeroplane is therefore comparatively insensitive to its direction of flight in pitch.

Thus the problem for the designer of an automatic elevator control is to detect changes in the pitch of the flight path so that such a disturbance can be directly corrected via the elevators.

This requirement involves the definition of a direction in pitch. No instantaneous aerodynamic device can sense that the flight path is inclined, nor can a gravitational device, paradoxical though it may appear to all of us who have been educated in the pre-Einstein school of dynamics. A gravitational device, for example a longitudinal inclinometer, derives its only controlling field from the extraneous force, in this case the resultant reaction of the air on the aeroplane and screw. The indication of the inclinometer, therefore, depends only upon the incidence of the aeroplane and the advance per revolution of the screw. Clearly, therefore, it is as insensitive as the aeroplane to change of direction of flight.

It would appear, therefore, that there is no known device except the gyroscope which is capable of detecting the required disturbance in its initial stage unless it be a device for detecting that the air speed or the barometric pressure is changing. The gyroscope is used in the Sperry and the Smith automatic controls, rate-of-change of air speed has been used in a very interesting design by Siemens and rate-of-change of barometric pressure was proposed some 12 years ago by one of the authors of the present paper.

The introduction of a gyroscope to detect pitch disturbances does not, however, end the difficulties of longitudinal control for the automatic control designer. The mechanism which is introduced to control the long period disturbance, insists on trying to control the short period pitching oscillation as well, a job for which it is not required (since the aeroplane designer has already dealt with this mode of oscillation) and for which it is rather badly equipped. Most of us have had experience of a learner attempting to steer a motor car or a yacht. The delay in his reactions causes him to apply all his corrections a little late, with the result that he causes the craft to hunt or weave in a disconcerting manner. So, with the automatic pilot, if there is any lost motion or delay in the application of the required elevator movement, the well behaved short period oscillation develops into an irritating hunt.

To avoid this the designer must increase the sensitivity of the valve by which the apparent movement of the gyroscope is detected and this in turn may lead to a spontaneous oscillation of the servomotor. This tendency to oscillate on its own is particularly apparent with pneumatic servomotors owing to the compressibility of the operating fluid. Electric servomotors have never proved satisfactory for the fundamental reason that their inertia is excessive when all the other difficulties of fine gradation of control have been surmounted. Hence, the Sperry Company have now adopted a hydraulic servomotor system requiring a

dual power supply, pneumatic for driving the gyroscopes and relay valves, hydraulic for the main servomotors. Many other designers have followed the Sperry practice.

The authors in designing the R.A.E. Mark I control, of which the Smith control is the commercial version, used a single power supply of compressed air and relied upon precision of manufacture of the detector valves and careful adjustment of the gearing of the control to avoid a quick period hunt of the aeroplane. Too high a gearing between the apparent movement of the gyroscope and the resulting movement of the elevators or a poor lay-out of the bowden follow-up cable from the servomotor to the gyroscope still leads to slight hunting in pitch, but the fault is remediable.

The next difficulty presented by the gyroscope is that no gyroscope is perfect and unwanted precessions always develop. Even were the gyroscope perfect, the rotation of the earth would lead to apparent precession and a departure of the gyroscope axis from the required attitude in relation to the assigned flight path. Thus the gyroscope in reality suffers from the same fundamental fault as the aeroplane, that it is not directly appreciative of a change in attitude in pitch. It follows that some means of controlling the precession in pitch of the gyroscope must be provided unless the pilot is to be burdened with the responsibility of making frequent adjustments in pitch.

Gravitational control is used in both the Sperry and the Smith automatic pilots. When these systems are considered in detail it is seen that there is an inherent difficulty in providing sufficient gravitational control in the Sperry system where a gyro-vertical is employed. Air speed control of the pitch precession would produce substantially the same stability characteristics as the gravitational control. Control of the pitch precession, in addition, by rate of change of air speed would possess the advantage that it would operate earlier, before the aeroplane had gathered or lost speed on the new flight path, and would thus permit a quicker recovery. It would, however, be considerably more complex than the very simple gravitational control provided in the Smith gear.

The fact that the gyroscope has to wait for a change of direction of the apparent gravity before a correcting precession is introduced is not of great importance because considerable disturbances of the gyroscope cannot be caused by bumps or, in the case of the Smith control, by alterations in course. Nevertheless, those who have had experience of flying with this form of control will have noticed that when the pilot effects a change of pitch there is an appreciable lag before the aeroplane settles to the new attitude. The transition takes place through a heavily damped oscillation, the period being about thirty seconds. The period and damping of this motion are practically independent of the stability of the uncontrolled aeroplane. Thus the aeroplane designer is not required to effect nice adjustments to ensure stability.

Lateral Stability.

The degrees of freedom involved in small lateral disturbances are ϕ, ψ and y.

Motion along the y axis, that is sideslip, is only coupled to the rotational disturbances by the yawing and rolling moments resulting from sideslip. Were the dihedral effect removed—this would require a slight negative dihedral—and the fin reduced to give zero weathercock stability about the yawing axis, the sideslip motion would be entirely independent and would take the form of a subsidence depending upon the lateral force due to sideslip. Although rotations in roll and yaw would still be coupled through the change in relative drag of the two wings when rolling and the change in relative lift when yawing, yet the exceedingly heavy damping in roll would cause this motion to separate out as a quick subsidence of rolling velocity. The yawing motion would also take the form of a subsidence, but the damping due to the yawing moment resulting from rate of yaw would be somewhat increased by the slight rolling motion introduced. The fourth root of the lateral stability equation would be zero, representing an

indeterminancy of the angle of bank. The aeroplane would continue in trim banked and sideslipping, the gravitational side force being countered by the lateral resistance to sideslipping. Such an aeroplane would not be unpleasant to control although it would require constant attention.

It is, however, customary to provide a considerable amount of dihedral whereby the sideslipping motion is directly coupled to the rolling motion. The motions then become so inter-related that it is no longer possible to associate them directly with the three degrees of freedom and it becomes exceedingly difficult to predict their characters.

It is not worth while to attempt to give a general description of the effects on these motions of varying the couplings under the control of the aeroplane designer. Mathematical analysis can be employed, but, as so many parameters are involved, numerical computation of the roots of the stability equation for a large variety of combinations of these parameters is required before a complete picture can be obtained of the effects of variations. This would generally require to be done for each aeroplane and the values of the derivatives involved would require to be determined by wind tunnel tests or by computation.

From such surveys of this kind as are available a few salient facts emerge. For example, the heavily damped rolling subsidence is so quick in relation to the other motions that it preserves its character in spite of any reasonable modifications of the aeroplane. Generally the yawing motion becomes involved with rolling and sideslipping to produce a short period oscillation. If the aeroplane is given sufficient rear fin to ensure that the yawing moment due to sideslip is stable, this motion is generally well damped, but, in an unpublished paper, Fraser and Pugsley have shown that excessive dihedral may destroy the damping, especially if the aeroplane is heavily loaded and possesses large moments of inertia. Lanchester drew attention to this form of instability in his book "Aerodynamics," and it has been discussed by other investigators in the field of aeroplane stability. For the present purposes it is sufficient to note that provided the dihedral is not too great the motion is a well damped oscillation.

For the sake of completeness it should be added that further reduction of the fin of an aeroplane possessing this form of oscillatory instability causes the motion to degenerate into two divergences, as in the case of the simple system with one degree of freedom. If, however, there is sufficient fin to avoid oscillatory instability, this more vicious instability, known as spinning instability, cannot arise.

There is still one root of the lateral stability equation to be accounted for. It is the root expressing the rate at which the aeroplane recovers—or does not recover—from a banked turn. Most aeroplanes when trimmed to fly straight will be approximately in trim when executing a slightly banked turn. Thus it may be expected that the rate at which this disturbance recovers or grows will be small, the motion being represented by a very small root of the stability equation. When this root is positive—the unstable condition—the aeroplane is said to possess "spiral instability."

The nature of this spiral motion can be readily understood from a consideration of the balance of yawing and rolling moments during the banked turn.

Considering first the rolling moments, there will be a tendency for the outer wing to continue to rise owing to its excess of speed over the inner wing. This is countered by the rolling moment due to an inward sideslip. Thus recovery will depend upon the rolling moment due to inward sideslip exceeding the rolling moment due to the rate of turn. Recovery can thus be aided by increasing the dihedral angle or by increasing the amount of sideslip in relation to the rate of turn. In yaw, the moment due to the inward sideslip, tending to increase the rate of turn, is countered by the damping moment due to rate of turn. The proportion of sideslip can be increased by reducing the yawing moment due to sideslip, *i.e.*, by reducing the amount of rear fin.

It may thus be said that, when an aeroplane is spirally unstable, the fin is excessive for the dihedral. Either may be altered to achieve stability, but the designer must be on his guard lest he introduce the much more objectionable oscillatory instability previously discussed. Nevertheless, if, in accordance with current practice, the dihedral angle is kept small, the short period oscillation should give no trouble provided the fin is kept large enough to ensure a slight weathercock directional stability.

From the foregoing description it will be appreciated that the aeroplane designer should and can provide that the aeroplane will be free from such vicious characteristics as spinning and oscillatory instability, but that the aeroplane is then necessarily insensitive to turning. It is, in any case, absolutely insensitive to direction in azimuth. It is these characteristics which the designer of an automatic control is required to correct.

The deficiency in " sense " of the aeroplane can most simply be corrected by a directional gyroscope controlling the rudder. Once it is introduced, the question of spiral instability of the aeroplane loses its importance. The short period oscillation remains satisfactory if the lag in the operation of the control is not excessive. The remaining difficulty is that the recovery from a banking disturbance may be slow and poorly damped. The motion is now a damped oscillation instead of a subsidence since an extra root is introduced into the stability equation by the fact that there is a moment due to a displacement in azimuth.

The characteristic lateral disturbances of an aeroplane with a gyroscopic rudder control are then a rapid subsidence of rolling velocity and two damped oscillations; a short period oscillation, which sometimes manifests itself as a slight hunt if there is appreciable lag in the application of the rudder, and a long period banking and yawing oscillation which may be poorly damped and which depends upon the dihedral of the aeroplane for the control of its period. With a normal amount of dihedral—say about 3°—the period is generally about 15 to 20 seconds.

The Sperry and the Smith controls depend upon a free gyro-azimuth. With this arrangement there are two known methods of improving the sluggishness in recovery from a disturbance of the angle of bank.

The most direct is to control the ailerons according to the displacement in bank as indicated by a gyroscope. In the Sperry control a common gyroscope, with a vertical axis of spin, is used for indicating both the pitch and roll disturbances. In the case of the Smith control, a common gyroscope is used for pitch and yaw, a second gyroscope being used for control of bank.

The second method of improving the banking characteristics, which was invented by one of the authors of this paper, is to incline the axis of the gyroscope used for control of the rudder. The effect is to cause an apparent azimuth displacement when the aeroplane banks, in such a sense that the resulting application of rudder induces a sideslip towards the depressed wing. The result is to call into play the restoring moment due to the dihedral and a damping force due to the resistance to sideslip. This results in an adequate shortening of the period, if the dihedral angle is not too small, while at the same time the damping is adequately increased. The damping of the short period oscillation is, however, reduced by a corresponding amount. For aeroplanes with a dihedral angle of about 3° or more a very successful control can be obtained in this way. Messrs. Smith have taken advantage of these ideas to market a two-axes control with a single gyroscope, inclined upwards towards the front, controlling the elevators and rudder.

When the aileron control is added, to make a complete three-axes control, the feature of the tilted axis of the directional gyroscope is still retained as it generally results in a considerable improvement of the damping of the longer period lateral oscillation.

The Smith aileron control has been designed to ensure flat turns under automatic control. This feature has been criticised on the grounds that the resulting

lateral acceleration is unpleasant to the passengers. Messrs. Smith can reply that this feature has been deliberately introduced to provide a stable platform for bomb-aiming or photographic survey work, and that, where comfort of passengers is the primary consideration, the two-axes control will ensure approximately correct banking during turns.

General Requirements of an Automatic Control.

From what has been said regarding aeroplane stability it will be clear that a pilot, human or automatic, requires primarily information as to direction in pitch and in azimuth, but that information as to lateral tilt is useful although not essential in view of the dihedral stability of the aeroplane.

Many designers, particularly in France, have designed controls depending upon the information derivable from wind vanes and pendulums. If these controls were mechanically perfect, so that the control movements corresponded exactly to the disturbances with no lag, the result would always have been achievable by the aeroplane designer by modification of the dihedral angle and of the size or position of the tail organs. It has been shown that these adjustments cannot produce really satisfactory stability. Thus all automatic stabilisers of this type can, at the best, do no more than correct an error in design of the aeroplane, while at their worst they may cause a previously well behaved aeroplane to hunt or even to execute an unstable oscillation.

To use, as one designer has done, a lateral pendulum in addition to a wind vane to control the ailerons through the agency of an electric servomotor is a particularly glaring example of this type of fallacious design—for the displacements of the lateral pendulum and of the vane are both measures of sideslip to which the aeroplane is directly responsive.

Rate-of-turn gyroscopes do not come in quite the same category as they may supplement the damping coefficients to an extent which would be difficult to achieve aerodynamically without an undesirable lengthening of the fuselage. Since, however, the slow longitudinal disturbance and the slow lateral disturbance both involve only slight rates of rotation, the extra damping, introduced mechanically, has little effect on these disturbances; it appears in the short period motions which are already adequately damped.

Cross-coupled rate-of-turn controls, for example, operation of the ailerons in response to rate of yaw, may modify the couplings which are not readily controlled by the aeroplane designer. By such means the character of the lateral motions may be considerably modified.

Rate-of-turn controls will, however, do nothing to prevent the slower disturbances. They must therefore be supplemented by other detectors, for example, an air speed indicator and a compass. A successful automatic pilot on these lines has been produced by Siemens. This control also incorporates a very pretty device which measures the rate of change of air speed whereby, as stated above, the long period pitch disturbance can be detected in its initial stage of inclination of the flight path. By these means excursions of the air speed can be kept within close limits, possibly as close as in the case of the authors' design, but the authors lack data on this point.

In selecting " free " gyroscopes as the detectors of disturbances, the authors were helped by the experiments of the late G. L. Smith and of P. S. Kerr, and also by the mathematical work of Gates and Garner, in particular, in adapting the classical theory of aeroplane stability to the controlled aeroplane.

General Description of the Smith Automatic Control.

This control is identical with the R.A.E. Mark I control designed by the authors of the present paper who may, therefore, be considered to be prejudiced in its favour. Nevertheless, it is proposed to describe this control in particular, as the authors are clearly more aware of its features than of those of any other design.

A detailed description has already been published in a series of articles in 1934 and 1935 in *The Aircraft Engineer*, by G. R. M. Garratt. It will suffice, therefore, to give now only a general description illustrated by schematic diagrams.

It has been mentioned that Sperry uses a gyro-vertical for control of the elevators and ailerons. It will be clear from what has been said that such a gyroscope requires gravitational control. This control must, however, be slow in action to avoid serious disturbance due to the displacement of the apparent vertical during a turn. The result is an undesirably slow recovery if the gyro-vertical is displaced from the vertical. It is understood that the Sperry Company make no claim that their control is suitable for photographic survey work. Possibly this feature of slow gravitational control is the reason for this modesty on their part.

The authors had in view from the beginning the desirability of ensuring quick recovery both in pitch and in roll after any disturbances of the gyroscopes. They

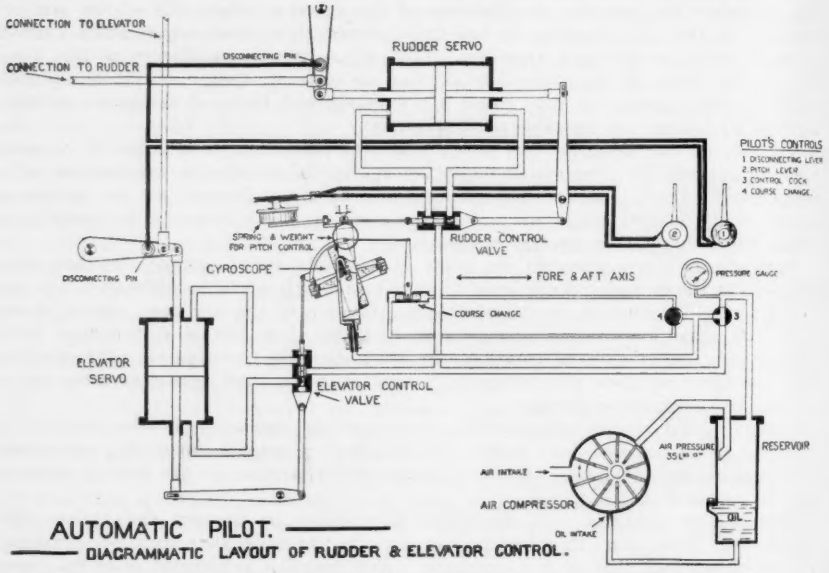

FIG. 2.

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therefore adopted the arrangement of a single gyroscope which is precessed in azimuth during a turn and of which the rotor axis always lies approximately in the plane of symmetry of the aeroplane for control of the rudder and elevators. Thus the gravitational control in pitch and in roll are made entirely independent, permitting high rates of control of the gyroscopes to be used in both cases. It will be seen later that the effect of centrifugal force on the aileron controlling gyroscope can be completely balanced out.

Fig. 2 is a diagrammatic illustration of the rudder and elevator control. The diagram is schematic and no attempt has been made to conform in detail to the actual design.

The gyroscope (shown in side elevation) is carried in a double gimbal system giving it complete freedom in azimuth and in pitch. The wheel is driven by air jets impinging on suitably shaped buckets cut in the periphery of the wheel. The air is led through the bottom gimbal bearing from a supply delivered at a pressure of 35lb. per square inch by a small rotary pump driven by the aeroplane engine

or by a windmill. The same supply of compressed air is fed to the two servomotors controlling respectively the rudder and the elevators via balanced air valves operated by connecting rods attached respectively to the outer and inner gimbal rings.

As stated previously the rotor axis is inclined upward towards the front for the purpose of moving the rudder valve when the aeroplane banks.

When either valve is displaced, by a deviation of the aeroplane from its assigned course, air is fed to the appropriate end of the relevant servomotor which proceeds to move the aeroplane control. At the same time the servomotor, through follow-up mechanism, moves the outer casing of the valve so as to restore the centralised condition of this member. The servomotor thus maintains a displacement proportional to the deviation of the aeroplane.

The servomotors are connected to the aeroplane controls by double lever systems whereby they may simultaneously be disconnected by the pilot at will by means of a bowden wire control (1).

Moments are applied to the outer gimbal ring by a spring loaded lever and by the weight of a mass attached to the right hand side of the ring. If these moments are not balanced the inner ring will precess about the axis of pitch and will thus correct the pitch attitude of the aeroplane until the moments are balanced.

By means of a bowden wire control (2), the pilot can regulate the strain of the spring and so adjust the trimming attitude of the aeroplane.

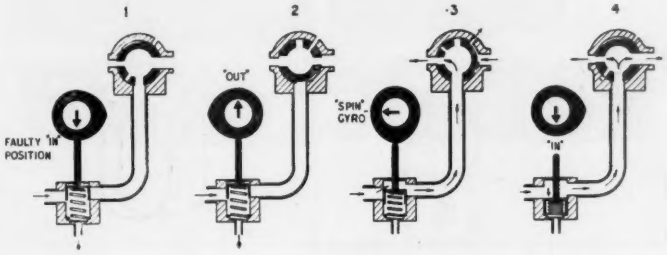

FIG 3.

DIAGRAMS OF SAFETY DEVICE TO PREVENT THE CONTROLS FROM BEING ACCIDENTALLY ENGAGED BEFORE THE AEROPLANE TAKES OFF.

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To alter course, the pilot operates the tap (4) whereby compressed air may be fed to either end of the course-change cylinder. The reaction on the piston of this cylinder is transmitted to the inner ring of the gyroscope, thus causing precession of the outer ring and so causing the aeroplane to turn in azimuth. To minimise unwanted precession about the axis of the inner gimbal ring, the connecting rod from the course-change piston and a curved arm attached to the inner ring are connected by a ball and socket joint, the centre of which lies approximately on the axis of the outer ring. Thus no appreciable moment about the outer gimbal axis, which would cause the gyroscope to precess in pitch, can be applied by these means.

The pilot's master control is the cock (3) whereby the air supply to the automatic pilot may be cut off thereby centralising the gyroscope and short-circuiting the servomotors by means not shown in the diagram. This cock also permits the air to be supplied to the spinning jets without being supplied to the servomotors, for the purpose of running the gyroscope up to speed before engaging the controls.

Fig. 3 illustrates the function of one of several safety devices which have been introduced as the result of experience gained in service.

The device illustrated (due to P. S. Kerr) is connected to the control cock illustrated in the previous figure. If the aeroplane takes off with the control cock in the " in " position the valve at the bottom will cut off the supply from the control cock and exhaust it to atmosphere as shown in the first diagram. The correct sequence of operations to engage the controls is shown in the other three diagrams. The cock should be put from the second position to the third position, " spin gyro," while the aeroplane is in flight. In this position the cam, attached to the cock, depresses the valve to seal off the exhaust and so admits the air to control cock. The air pressure then depresses the valve against its spring. When the cock is subsequently turned to the " in " position the air is admitted via the cock to the spinning jets and to the servomotors as shown in position 4.

Fig. 4 is a schematic diagram of the aileron control. The gyroscope is shown in rear elevation and also in perspective in the inset.

The rotor is carried with its axis athwartship. The axis of the outer gimbal ring lies fore and aft while the axis of the inner ring is vertical. A movement

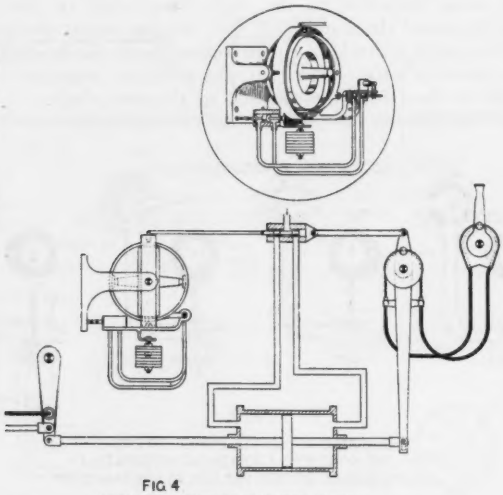

FIG. 4
SCHEMATIC DIAGRAM OF AILERON CONTROL

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in roll of the aeroplane causes relative movement of the outer gimbal ring and thus operates the valve shown connected to the ring. As in the case of the rudder and elevator controls, the resulting movement of the servomotor operates a follow-up which centralises the valve when the required amount of aileron movement has been applied. An adjustable member in the follow-up mechanism, operable by a bowden wire control, permits the pilot to adjust the position of the servomotor in relation to the gyroscope so as to correct any error in trim of the aeroplane. The same double lever and spring catch mechanism for disconnecting the control is provided as in the case of the rudder and elevator controls. The centraliser which also short-circuits the servomotor is not shown in the diagram.

Gravitational control of the attitude of the gyroscope is provided by the weight attached to the bottom of the outer ring which operates in conjunction with a small valve which is operated by relative movement of the inner ring and controls the reaction of a small servomotor operating to apply a torque to the outer ring.

These details are illustrated in perspective in the inset of the diagram. They operate in the following manner.

If the rotor axis is not level, the weight applies a torque to the outer ring. This causes a precession of the inner ring about the vertical axis. The resulting displacement of the valve causes the servomotor to apply a torque to the outer ring which counters the torque applied by the weight and prevents further azimuthal precession of the gyroscope. The opening of the valve, however, lifts one or other of two light spring arms from an adjustable stop and so causes a slight torque about the vertical axis. This torque precesses the gyroscope slowly about the outer gimbal axis until this ring lies in the vertical plane when the weight ceases to operate.

The somewhat complex sequence of these operations is required to ensure that the gravitational control will operate accurately during a turn as well as in straight flight. During a turn the centripetal acceleration of the weight causes the gyroscope to precess in azimuth at the same rate as the aeroplane is turning. Thus, providing the outer ring is vertical, there will be no movement of the valve and its associated spring and the lateral level of the gyroscope will not be disturbed. If, however, the gyroscope is not level it will subside to the level position during a turn in exactly the same way as during straight flight.

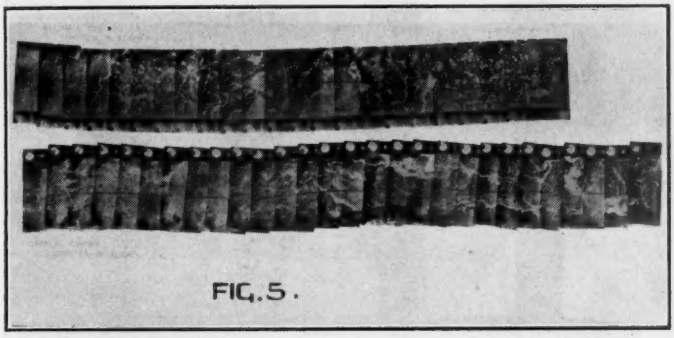

FIG. 5.

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This nice arrangement whereby the displacement of the apparent vertical during a turn does not displace the lateral level of the gyroscope, depends upon a predetermined relationship between the speed of the aeroplane and the speed of the rotor, for the former controls the centripetal acceleration and the latter the gyroscopic reaction against which it is balanced. The system is tuned by adjustment of the vertical distance of the weight to suit the operating speed of the aeroplane in which the control is to be installed.

Several important details have been omitted from both the schematic diagrams for the sake of clarity. Thus the follow-up mechanism should have been shown adjustable to permit adjustment of the " gearing " of each control to suit each individual design of aeroplane. After installation, these follow-up ratios may require adjustment to obtain the quickest recovery from any disturbance.

It should be noted that, whereas the gyroscopes are gravitationally controlled in pitch and bank, no azimuthal control other than the course-change-cock operable by the pilot has been shown. Messrs. Smith have, however, produced a relay compass which can be harnessed to the course-change system so as to relieve the pilot of the necessity of occasionally resetting the course. For such work as photographic survey photography, the operator can be supplied with a graded self-centring control operating pneumatically on the course-change cylinder. He can thus make the most delicate adjustments to the rate of turn as required.

PERFORMANCE OF THE R.A.E. MARK I AUTOMATIC CONTROL.

It will be clear that, since the purpose of the automatic control is to suppress unwanted angular deviations of the aeroplane, the performance can best be specified by the magnitude of the excursions under automatic control. These excursions have been examined in a statistical manner by reference to an independent gyroscopic recorder and by means of photographs of the ground. By these means the instantaneous deviation about the selected axis can be determined at random intervals. The result can be expressed by what is called the " probable error."

If all the errors are arranged in two equal groups in such a manner that all the errors in the second group are greater than any of the errors in the first group, the probable error lies between the greatest error in the first group and the least error in the second group. In other words, there is an equal probability of any error selected at random being greater than or less than the probable error.

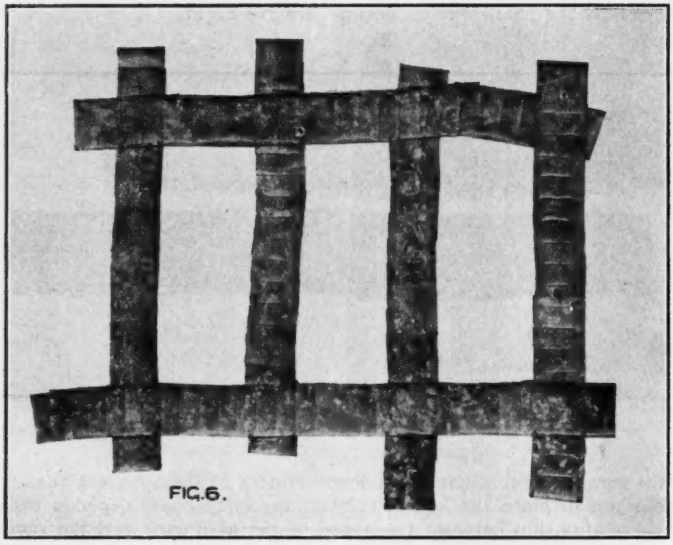

FIG. 6.

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Experiments on several aeroplanes operating under the Mark I control under normal atmospheric conditions at 10,000 feet altitude, have shown that the probable error about any of the three axes lies between one-fifth and one-quarter of a degree.

As a result of this extremely high precision the control is admirably suited for photographic survey work.

The Report of the Air Survey Committee No. 2, 1935, records the results of a comparison of the methods of automatic pilotage with the Mark I control and a highly skilled human pilot. This comparison was made during the Transjordan survey of 1930-31. The report states:—

> " After photography had been begun advantage was taken of this survey being in progress to try out the value of gyroscopically-controlled aircraft for survey photography and much of the area was re-photographed with this machine. The main interest of the survey of this area lies in the results obtained with the automatic pilot."

Commenting on the results obtained the report states:—

"It (the automatic pilot) provides a means of producing high-class survey photography without the previous lengthy training of the pilot, and owing to the accuracy of the flying it can produce work quickly, which, in cases where suitable weather is not the rule, is of supreme importance. Moreover, the standard of photography and freedom from tilt is vastly superior to that produced by the best trained pilot using manual control. Fig. 40 shows a reduced copy of two strips taken under exactly similar conditions, one by the automatic pilot and the other by manual control. They have been put down on a principal point traverse and the difference between the two is immediately apparent."

After further explanatory statements as to the facility of plotting the results obtained with the automatic pilot, the report concludes that:—

"The flying of the automatic pilot is so superior to that of the piloted aircraft for survey purposes that it would seem most undesirable nowadays to attempt any air survey photography without its assistance."

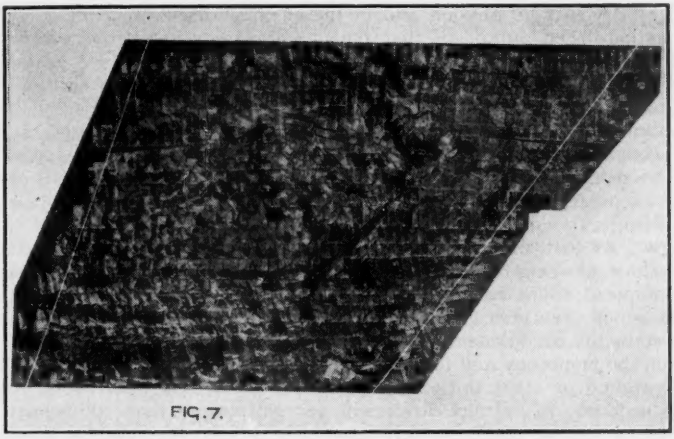

FIG. 7.

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So far as the authors of the present paper are aware, no other automatic pilot has been found to offer these advantages.

Fig. 6 shows a grid set out from the first photographs of an area about 25 miles long, produced with the aid of the Mark I automatic pilot. Such a grid is produced as the first stage in the survey of an unmapped area and is used to define the key points for the subsequent runs to fill in the area.

Fig. 7 shows an ambitious effort to cover a small mapped area with large scale photographs for map revision. A series of 27 overlapping runs were laid out on a map and the photographer, who had had no previous experience of this class of work, was required to navigate the aeroplane on the required tracks by map reference. Since the scale was such that each photograph covered only 2,500 feet laterally, the fact that only two narrow strips were missed was a very creditable performance. The absence of banking errors in consequence of the steering correction illustrates one of the advantages of the R.A.E. aileron control for this class of work. The whole series of over 1,300 photographs, covering an area of nearly 100 square miles was produced in 12 hours' flying.

There appears to be a fairly general misapprehension that such precise pilotage involves brutal handling by the automatic pilot and that the aeroplane, its controls

and its occupants are subjected to undue strains. In a series of articles published in *L'Aeronautique* last year by Haus this criticism is forcibly advanced. The author, on theoretical grounds, maintains that a gyroscopic elevator control does not reduce vertical acceleration in bad weather. He goes on to say that, in spite of this disadvantage, several gyroscopic stabilisers have invaded the commercial field, amongst them being the Sperry and the Smith controls.

He is, of course, under a misapprehension because vertical accelerations, belonging as they do to the short period motion of the aeroplane, are inevitable unless the aeroplane were to rotate instantaneously to every gust or unless the wings were made flexible in torsion as are the wings of a bird.

The gyroscopic controls effect their purpose with extraordinarily small control movements, far smaller than those made by the most skilful pilot. They achieve this because the gyroscopes can detect the disturbances at an earlier stage and, as the automatic pilot is never inattentive, the corrections are applied at an early stage when small control movements will suffice. Naturally small control movements imply small stresses in the control systems.

The author of the articles in *L'Aeronautique* may have been influenced by the unfortunate statements made in the paper read before this Society at its first meeting of the 1935-36 Session and in the ensuing discussion.

The distinguished author of that paper suggested that " the automatic pilot will doubtless be a valuable asset when still larger aircraft are produced. Its present shortcomings," he went on to say, " are its cost, weight and the necessity of designing the aircraft control layout specially to take the stresses it imposes."

Automatic controls have been fitted to dozens of types of British aeroplanes, but the authors are not aware of a single instance in which the control systems had to be redesigned on account of the stresses involved. Indeed, were such redesign necessary, the aeroplane concerned would not have been airworthy for manual flying.

In regard to cost and weight, of course these terms are relative. It may be that for short journeys the cost and weight of an automatic control may render it uneconomic. There can, however, be no doubt that, for flying considerable distances in all weathers, the automatic control is well-nigh indispensable. It will maintain the aeroplane accurately on the assigned course while the pilot is freed from the monotony and fatigue of continuous flying and therefore is available for navigational or other duties. This it will do in fair weather or foul. The resulting economy in mileage flown will generally more than compensate in fuel for the extra weight carried which, after all, is less than that of a man. The power absorbed by the required engine driven compressor under cruising conditions is only about 2 h.p. Thus the cost in weight of fuel amounts only to about 1lb. per hour flown.

Discussion.

The President: They had listened to a masterly exposition of a difficult subject. Mr. Meredith had had to shorten by a good deal what was in the paper, and in shortening he thought that sometimes he had had to make statements which, when the paper was read, would be found to be qualified in a way that could not be done in an abstract. What he felt bound to say was that he thought Mr. Meredith had been much too hard on the pendulum. After all, the apparatus he had described had its own gravitational element. The difficulty with the pendulum was that its period was usually too short. If the pendulum could have a period much longer than the roll or pitch of the aeroplane, it would do everything the gyroscope had to do and would do it very much better. The main disadvantage of the pendulum was not that it was controlled by gravity, but that it could not be given a sufficiently long period.

A very careful study of this subject was made during the war. His own first experience of the gyroscope stabiliser was in 1915 at the Naval Air Station at Calshott. They had had sent down to them a Sperry automatic stabiliser. It

was a queer looking little thing with four gyroscopes in it, and an electrical relay. Of course, the aeroplanes at that time were in much too tender a condition for the application of gyroscopic stabilisation. Then there came an effort to build in the Naval Air Service an enormous seaplane, with a kind of *camera obscura* in it, and fitted with a pendulum containing a gyroscope—a mixture of the two—providing damping control with a suitably long period. That seaplane came to an unfortunate end, and its gyro pendulum never saw any use at all.

The first time he saw a Sperry gyro horizon was just after the war, when he had to go over to New York and saw Mr. Sperry. Mr. Sperry, who was then an old man, received him charmingly; no one who met him could help liking him. He showed the first of these gyro horizons, which, as far as he could see, was very like the Sperry construction of to-day. He thought it a beautiful piece of mechanism, and later on it formed the " brain " of the Sperry automatic stabiliser now used.

He did not think he had anything else to add to the discussion, beyond saying that anyone who supposed that this was a simple subject was greatly mistaken. Anyone who supposed, further, that having got a mechanism of this kind elaborated in theory, it was quite a simple matter to make a pilotless aircraft which would fly by itself, was remarkably mistaken. The application of a complicated mechanism of this kind, however beautifully designed and reliable, to the conditions of flight, with no one on board to rectify anything that might go wrong, was one of the most difficult problems he had ever come across.

Dr. A. L. Rawlings: He desired to congratulate the authors on the paper which had given him much pleasure, because he had been interested in their designs for a great many years. He thought it was in 1926, or 1927, that he saw some of the authors' early efforts, and he had watched their work since with great interest, sometimes at close hand, but more often from a distance. He knew a little of the tremendous practical difficulty with which the subject was surrounded, and of the number of things which would never occur to anyone who simply looked at it from an academical point of view. There were various things, such as the transferring of air pressure through bearings, and all manner of small details, the importance of which was never realised until one found one's self hard up against them.

Fortunately for himself, he had also been in a position to watch the development of the Sperry Gyroscope Co.'s instruments. He was at one time interested in their four-gyro machine, designed in 1916, of which the principal recollection he now had was the rather appalling noise—a kind of protesting groan—which it used to make. At the same time he felt, as he got nearer to years of discretion, that although in this particular case the design was based very largely on scientific principles, it was nevertheless dangerous to predict too much from mere theory. About ten years ago when the small gyro horizon, now incorporated in the Sperry pilot, was coming into being in its present state, he made a rather foolish prediction. He said that this was a gravity controlled gyro, and that it would be affected by lateral acceleration, and he did not think that a 90° turn could be made in a moderate time without sending that gyro off by several degrees to one side. He was told that he had better go up in a plane with it and see for himself. At that time he had never been up in an aeroplane, and a flight was arranged. He went up with an American Army airman, and on the way they discussed the dynamics of flying aircraft, and he made another very foolish prediction, that the pilot could not bank the aeroplane 90°. Well, the instrument and himself were put into the plane, and he proved that he could bank 90°—at any rate, more or less 90°, as indicated by the horizon, though to his own sensations it seemed more like 490°. At the same time the Sperry instrument was not appreciably disturbed. However, what he had in mind was this, that he was inclined to think that some of the statements in the paper about the limitations of the Sperry pilot were not always borne out in practice.

The pendulum device had got peculiarities which were rather difficult to explain. One of them was that it had a discontinuous action and when lateral acceleration existed to a certain degree the pendulous effect did not increase in the same proportion as it did for small angles of inclination. That was largely an answer to the problem.

It might be that the Sperry Company had not claimed that their machine was suitable for photography, and he was not really in a position to say as to that. He ought, perhaps, by way of introduction, to have stated that he was not at the present time in the permanent employment of the Sperry Company; nevertheless, he was very much interested in their work.

He might argue that the very clever aileron control gyro, shown in Fig. 4 of the paper, was open to a very similar objection to the pendulum. It was stated that the pendulous weight had to be set to the speed of flight. That must surely be the ground speed and not the air speed, and the ground speed would vary within very wide limits according to the weather and the direction of flight. It might easily vary, he imagined, by 20 per cent. Was he not right, therefore, in thinking that if the ground speed was 20 per cent. different from the speed at which the pendulous weight was set, after a turn of 100°, the machine would be 20° wrong? That was how it appeared to him at the moment.

However, as he had already said, it was very dangerous to make any kind of predictions, though another prediction that possibly might be made, was that it was not beyond the bounds of possibility that someone might overcome all these difficulties and make nonsense of the objections he had tried to illustrate.

He wished to say how much he appreciated Fig. 1 in the paper. It was one of the cleverest things of its kind he had ever seen, and it struck him as particularly ingenious.

Another invention of the authors' which he particularly admired was the rudder and elevator control of their pilot. The tilted axle of the gyro fulfilled so many requirements in such a simple way that he had always regarded it as one of the prettiest inventions he had ever come across.

Mr. S. H. Evans (A.F.R.Ae.S.): With regard to the relative merits of the Sperry and the R.A.E. types, could the Sperry Company give detailed weights and the latest information regarding their construction and would the authors of the present paper give the corresponding data with regard to theirs?

Major R. Ll. Brown (of the Ordnance Survey): He had very little right to speak on this subject, because he himself was a surveyor, but what interested him in this particular machine was the use to which a surveyor could put it. It was especially interesting that Mr. Meredith had used in his paper illustrations from surveys, with two of which, incidentally, he (the speaker) had been intimately connected. Now it was an extremely fortunate thing for the surveyor that the aiming of a bomb sight, was almost identical with the aiming of a camera. Of course, the surveyor did not want to go dropping bombs about the place—that was the last thing he wanted to do, because his object was to keep it quite private that he was up in the air at all. But these machines had been developed, largely from the bombing point of view, and they seemed likely to be of enormous use to the less affluent surveyor.

The surveyor knew one thing about a vertical photograph, namely, that it was probably not vertical. He knew where the centre of the photograph was, but he did not know, and could not find out by any simple means, the plumb point of the photograph at the moment of exposure. There were no simple means of finding that out, though the relative tilts between photographs could be determined by complicated and expensive machines. For simple methods of surveying it was necessary to assume that the centre of the photograph was the plumb point. The plumb point was of so much interest to the surveyor because of the undulations of the ground, for the distortions due to those undulations were radial from the plumb point. There was another point called the iso-centre, and from the iso-centre the distortions due to the tilt of the photograph were radial. The

automatic pilot tackled the problem in another way. It tried to make these points coincident—to make the plumb point the centre of the photograph by maintaining the axis of the camera vertical. This was by far the more desirable method from the surveyor's point of view.

There had been shown on the screen the two strips of photographs (Fig. 5) and to him these were very remarkable. He saw the flying for that survey, and it came to this, that quite apart from the great navigational advantages, flying of this type of accuracy not only simplified the surveyor's task in plotting, but also enabled him to dispense with a large percentage of the ground control that would otherwise be necessary. Thus it could be seen from their point of view as surveyors this invention was of very great interest indeed, and one could only congratulate those who had spent so many years of patient study and research in producing it.

Lieutenant E. H. THOMPSON, R.E.: He had been working for the last 18 months on one of the expensive machines to which Major Brown had referred, and he had put through the machine three strips of photographs which had been taken at various times with the Smith Automatic Control. He had determined the tilts of each photograph and these tilts are given in the appended table. The units in the table are degrees and decimals of a degree. Strip I was flown in 1935 by an old Virginia aircraft flying at about 11,000 feet. This was the ceiling of the aircraft and the fact that it was flying at full throttle in order to maintain this height accounted for the comparatively large fore and aft tilts. Naturally this would not affect the lateral tilts which were quite good. Strip II was flown from 12,000 feet with a more modern machine (D.H. Dragon). The most amazing results were those of Strip III which had been flown in Canada at a height of 18,000 feet.

Strip I.		Strip II.		Strip III.	
Lateral.	Fore and Aft.	Lateral.	Fore and Aft.	Lateral.	Fore and Aft.
+0.15	+1.08	−0.33	−0.14	±0.00	−0.16
+0.14	+0.17	+0.12	−0.27	−0.05	−0.06
+0.62	+0.48	+0.22	−0.25	+0.24	−0.21
+0.05	+2.27	±0.00	−0.11	−0.11	+0.24
−0.46	−0.90	−0.18	−0.54	−0.02	+0.02
−0.25	−0.66	−0.03	+0.28	+0.53	−0.06
±0.00	−0.23	+0.12	±0.00	+0.16	+0.06
−0.03	−0.88	+0.08	+0.53	−0.09	+0.18
−0.13	−0.62	+0.03	+0.03	+0.02	±0.00
−0.10	−0.37	—	+0.47	—	—
—	−0.43	—	—	—	—
Probable errors—					
±0.19	±0.64	±0.11	±0.23	±0.15	±0.10

Mr. FAREY JONES: He drew attention to the fact that a distinguished visitor was present from Amsterdam having come specially over to hear this lecture and having a very considerable knowledge of automatic pilots. He asked that he might be allowed to speak.

Mr. LUMN: He thanked the Society for giving him the opportunity of spending a very useful evening. In Holland a good deal of experience was being acquired with regard to the automatic pilot. The Sperry automatic pilot was being used and was giving very great satisfaction. The Dutch Government had supported the enterprise. It was now possible to fly in much worse weather than could be done before on the all-India route, and the safety was much increased. With these machines the service was always on time. With regard to the pendulum, with the Sperry automatic pilot, they had made about two turns in one minute and after that had been done the aeroplane was slightly banked.

Captain P. BAILEY: There was one point in this lecture which had been omitted, he did not know whether by accident or otherwise, namely, the question of aeroplane stability in relation to control stability or stability of the machine under control. In such work as he had done on this question, which was quite considerable, he had found control stability the most important thing, being more important than machine stability. Perhaps Mr. Meredith could tell them whether he was considering lack of control stability or the actual inherent stability in the machine.

Furthermore, there was a point in the printed paper which he did not think was stressed in the lecture, namely, the use of two or more horse-power, as was done in the operation of automatic control. He could not quite conceive why this power was necessary, because, when all was said and done, one man-power ordinarily piloted the machine, certainly not two horse-power. In his own case he had been flying now for some years on an automatic control which had consumed 0.2 horse-power.

With regard to the cut-out on the control, in extremely rough weather sometimes a small or medium machine would take up a bank of 50° against the control, and were it automatically cut out the machine might get on its back. Where the control was cut out because it was moving too fast the machine might become inverted or in case of an outboard engine out, spin.

The reason why he had mentioned the air stability question was because as he had discovered from his own experiments, there were not a great many people who could give designers a line on this subject as to what was wanted. He carried out test work on two aeroplanes, one of which was unstable, and yet was all right in calm weather, but in rough weather was not. The difference between the two was that one aeroplane was stable on its controls and the other was not. It was the control that was doing the harm, not the aeroplane. It took him quite a long time to learn that the automatic control could not think. That was his main reason for stressing the point.

A point which he intended to stress further was that the mere fact that because a machine was controllable by a pilot that was no proof of its control stability, *e.g.*, blind flying a machine with serious aileron drag.

REPLY TO THE DISCUSSION.

With regard to the Chairman's remarks on pendulums he must accept his correction. What he had meant to be dogmatic about was any device which indicated the instantaneous position of the apparent vertical. He assumed, when he referred to pendulums, a perfect pendulum that did not waggle, that always pointed in the direction of apparent gravity. If there were such a pendulum as that, it would be of no use for the detection of the disturbances of an aeroplane. The long period pendulum was of value for this purpose just so far as it did *not* respond to the gravitational field. The gyroscope he regarded as the practical solution of the problem stated in those terms.

Dr. Rawlings had mentioned that he had been surprised that the effects of centrifugal force on the Sperry artificial horizon were so slight and he had explained that this was due to the graded pendulum control. The present speaker would suggest that the objection to a gyro vertical was that the pendulum control was necessarily weak however it was graded and that in consequence recovery was necessarily slow after any disturbance. He thought it was true to say that with the R.A.E. lateral gyroscope of Fig. 4 it had been found practicable to use a rate of erection, for small disturbances, giving a recovery time of about a fifth of that of the Sperry gyro vertical.

Another point mentioned by Dr. Rawlings was that the R.A.E. aileron gyroscope was subject to an error owing to the differences between air speed and ground speed. The speaker thought that was a fallacy. The air speed was the only factor with which they were concerned. The air was the medium in which they operated, and the effect of the wind to an observer in the aeroplane

was merely that the ground was travelling. That had no effect whatever on the dynamics of the aeroplane. If Dr. Rawlings would think it out again in relation to axes fixed on the ground, making due allowance for the change in speed and track with change of course, he would no doubt agree with the deductions made in relation to axes fixed in relation to the air. It was a case of relativity.

It was agreed that an error was introduced during a turn if the air speed differed from that for which the unit had been tuned. After a prolonged turn the aeroplane would be banked by an amount which could be calculated as the proportional error in speed multiplied by the natural banking angle of the turn. On resuming straight flight the gyroscope would subside to the true level fairly quickly. The erection rate was, he thought, 10° a minute.

He welcomed the very illuminating exposition of the surveyor's problems from Major Brown and his kind remarks, also the interesting figures given by Lieutenant Thompson supplementing the earlier figures which he had given of the degree of stabilisation under the R.A.E. control.

Captain Bailey had asked a number of questions, but he must apologise to him because he had heard him imperfectly. He thought he had asked him whether the important thing was the aeroplane stability or the stability under control. The important thing undoubtedly was the latter. Their experience with the automatic pilot had been that for all normal variations in aeroplane stability, it was of no importance whether the aeroplane was stable or unstable before one controlled it.

If, however, Captain Bailey had been referring to the stability of the control itself, he was afraid he could not consider the stability of the gravitationally controlled gyroscopes by themselves. The gravitational controls depended upon the correlation of the gyroscopes and the aeroplane.

The variation in pitch during a turn under the two-axes control had also been mentioned by Captain Bailey. The omission of the aileron control did lead to an error in pitch as the gyroscope was being precessed about an inclined axis whereas the aeroplane was turning about the vertical. The effect, however, was not cumulative as the gravitational control caused the aeroplane to trim at a new angle in pitch. The order of the error was such that the aeroplane might gain about five or seven miles an hour during a prolonged turn; the effect was, however, proportional to the rate of turn.

Captain Bailey was a little sarcastic about horse-power. One of the difficulties was that in the case of the engine-driven compressor they wanted the thing to function even during a throttled glide, when the engine was barely ticking over. They had to gear their compressor to the engine to give the required delivery at a speed of 700 or 800 revolutions a minute. If they could have an infinitely variable gear that kept the speed of the compressor at that minimum required speed no matter what the speed of the engine, then the power consumed would come down to the practicable proportions that Captain Bailey desired. But the unfortunate compressor was over-run. It would do its job at 700 revolutions, but it was run up to 3,000 and it was under those conditions that it took the excess of horse-power mentioned in the paper.

The automatic cut-out was also mentioned by Captain Bailey, as possibly leading to a condition in which the last state was worse than the first, if the cut-out took place during a violent disturbance. Their cut-out, however, was only on the rudder and the elevator; it had not been necessary, from the point of view of airworthiness, to introduce it on the ailerons. Flying in weather conditions in which the aeroplane was subjected to such gross disturbances as Captain Bailey suggested, the pilot would have his hands on the controls ready to deal with any emergency. He had not heard of any case in which anyone had been inconvenienced by the automatic cut-out.

Two other speakers had asked for data as to weights and prognostications as to what might happen in the future. It was difficult to give data on weights of automatic pilots as the installation weights varied widely between one aeroplane

and another. An automatic pilot might weigh, say, 80lbs. complete in the laboratory, yet when installed in an aeroplane the total addition of weight might be as great as 140lbs. The increase was largely due to structural modifications required to withstand the reactions to the forces exerted by the servomotors and to extra lay shafts and levers which might be required to transfer the movements. Such increases were primarily due to the fact that the automatic pilot was being installed in an aeroplane which had never been designed with a view to such an addition. Thus when the aeroplane designer, starting *ab initio*, provided a suitable position for the automatic pilot, most of this parasitic weight could be avoided. He would not like, in the circumstances, to state any of the estimates of the installation weight of the Sperry pilot which he had heard, but the R.A.E. Mark I pilot, he believed, weighed 80lbs., and the complete installation anywhere between 120lbs. and 180lbs., according to how the installation system had been worked out. He thought he could say that, given an aeroplane designed to receive it, something fairly close to 100lbs. would have to be installed. He thought also that by new designs it ought to be possible to cut that figure considerably further, and he would say that it was not inconceivable that a satisfactory automatic pilot might be designed to instal at a weight of about 40 to 50lbs. That was not an impossible thing in the not too distant future. That was about as much as he would like to say on that point.

The PRESIDENT: They had had a very interesting lecture on a difficult subject, and although the speaker had been Mr. Meredith, the work was the joint effort of himself and Mr. Cooke, and the thanks of the Society were due to them both.

AT HIGH ALTITUDE.

By F. W. Lanchester, LL.D., F.R.S.

Part II.

Summary.

In the present paper (Part II) the engine, and more broadly the power plant, is considered in its relation to altitude. The discussion hinges mainly on the question of supercharge. After a brief reference to the various types of supercharger the author opens the discussion on an ideal basis, in which the supercharger is supposed to be 100 per cent. efficient, and the atmosphere is treated as adiabatic, as was at one time supposed. Then the "International Standard Atmosphere" is introduced as modifying the conditions, and after that the question of supercharger efficiency is dealt with. The author treats this on the basis of a law of adiabatic type but with a different index, and shows that this treatment gives an efficiency varying from approximately 60 to 70 per cent. as a function of altitude.

The difficulties connected with supercharge as affecting temperature, having been made clear, the subject of inter-cooling between compressor and engine is dealt with at length with the aid of thermodynamic diagrams. Then the propeller is discussed, and the case for variable pitch made clear.

Finally, the subject of surface cooling is dealt with, applied both to the engine and to the inter-cooler.

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§12. The Power Plant.

As concerns the relations of power (h.p.) and altitude the discussion has so far been confined to the needs of the case, that is to say, the power required; the means of generating and transmitting that power have next to be considered.

In this we are not faced with a single problem capable of being stated in precise terms, but with a number of problems and a number of variants. To eliminate one of these we shall in the first instance stipulate that the propeller is of fixed pitch.

We have seen with reference to Fig. 8 that the conditions which prevail at high altitude (for any aeroplane "in being") are associated with a demand for greater power[1] than at sea level; on the other hand, we know that a normal internal combustion engine, in which the weight (mass) of the charge is proportional to the density ρ, is capable of giving less torque, and less power, as the altitude becomes greater. Logically there are two methods by which this incompatibility may be met. The accepted solution to-day is the supercharger; but, during the War, when the mechanical difficulties of the problem had not been satisfactorily solved, the author pointed out that if an engine were *designed* for high altitude, and were run at low altitude under throttle, a similar result could in effect be reached. Obviously there is a limit to the extent to which cylinder diameter can be increased (the other features of design remaining unchanged), both on account of bulk and on account of the ability of the piston to resist inertia stresses. It is worthy of remark that if we had had to deal with an atmosphere of two or three times the present density at sea level, the simple expedient of thus designing for high altitude would have served every useful purpose.

[1] The demand is for a *constant torque;* the increase in h.p. is due to the higher optimum speed.

§13. The Supercharger.

It is impossible in this paper to deal with the different types of supercharger, or with the mechanical features by which they are characterised, in other than general terms. Amongst others there are two main types of geared supercharger, namely, the mechanical blower[2] and the centrifugal or turbo-centrifugal fan.[3] The latter type is sometimes driven by an exhaust gas turbine.[4] We are now more especially concerned with the *characteristic* of the supercharger as judged by the relation of engine torque to altitude. This appears to depend very much upon the system adopted, and it cannot be clearly stated because revolution speed affects the issue. Even in the case of a gear-driven blower this is so; for, although the metering of the charge is positive, the volumetric efficiency, owing to leakage, varies up to a point; it improves with speed. Where there is not the same positive metering of the charge the relation of revolution speed to volumetric efficiency is, from a theoretical standpoint, more complex. Furthermore, when the supercharger is of the fan type driven by an exhaust turbine, there ceases *a priori* to be any direct connection between volume and revolution speed, and appeal has to be made to the test bench.

Under these conditions it is necessary to proceed on the basis of an assumption, and this will be that the induction manifold is brought to such pressure as will give sea level density[5] up to some limiting height. Could we at the same time postulate that the charge when entering the induction pipe is brought to sea level temperature, then the sea level torque curve as given on the test bench would apply at all altitudes up to that limit for which provision is made. This question of temperature is the crux of the matter, and therein lies the main difficulty.

§14. The Temperature of the Charge.

A supercharger, otherwise a compressor, would, if it were perfectly efficient, give a true adiabatic compression, pressure and temperature rising in accordance with the adiabatic law. This does not mean that such a compressor would be perfect for the purpose intended; it might be better (if it were possible) to design a compressor to function isothermally; this not being feasible, the adiabatic condition is taken as datum and a compressor is said to have an efficiency represented by the theoretical temperature increase, as calculated on the adiabatic basis, in terms that actually observed. So defined it is generally stated that a supercharge compressor, or blower, has an efficiency ranging from 60 to 70 per cent. The comparison is instituted on a volumetric basis, *i.e.*, the adiabatic condition is:—

$$t_1/t_2 = (v_2/v_1)^{\gamma-1}.$$

The question of efficiency will be discussed later; for the present we shall consider the ideal case of a supercharger 100 per cent. efficient.[6] Referring to Fig. 9 which represents the cycle of operations of a supercharged engine as a single diagram, we see that from local temperature and pressure (which depend upon the altitude), compression takes place adiabatically until the full compression pressure is reached within the cylinder of the engine. At the point a according to our assumption the pressure has been brought up to that at sea level and the temperature has also been raised. Now we are assuming provisionally that the supercharger is adiabatic, and were the troposphere isentropic,[7]

[2] There are two types of mechanical blower, both of which are considerably used, namely, the Rootes type, and that with a single rotor with vane. Between these it is not necessary here to make a distinction.

[3] The combination of centrifugal and turbo action results in a more constant delivery than either separately.

[4] Cf. §14 (last paragraph).

[5] This is not the same thing as *constant pressure*. Temperature plays a part.

[6] On the convention that 100 per cent. efficiency corresponds to adiabatic compression.

[7] Or adiabatic (same thing), as at one time supposed or assumed.

the temperature increase would be exactly the same as though the charge had been sealed up in a balloon envelope and brought down to sea level, that is to say, pressure and temperature would be related in the supercharger exactly as they are in the atmosphere itself. *If this were true*, when the charge is fed into the induction system at sea level pressure, it would also be at sea level temperature[8] and density, so that, under the hypothetical conditions (represented by the solid graphs in Fig. 9) the working temperatures and pressures within

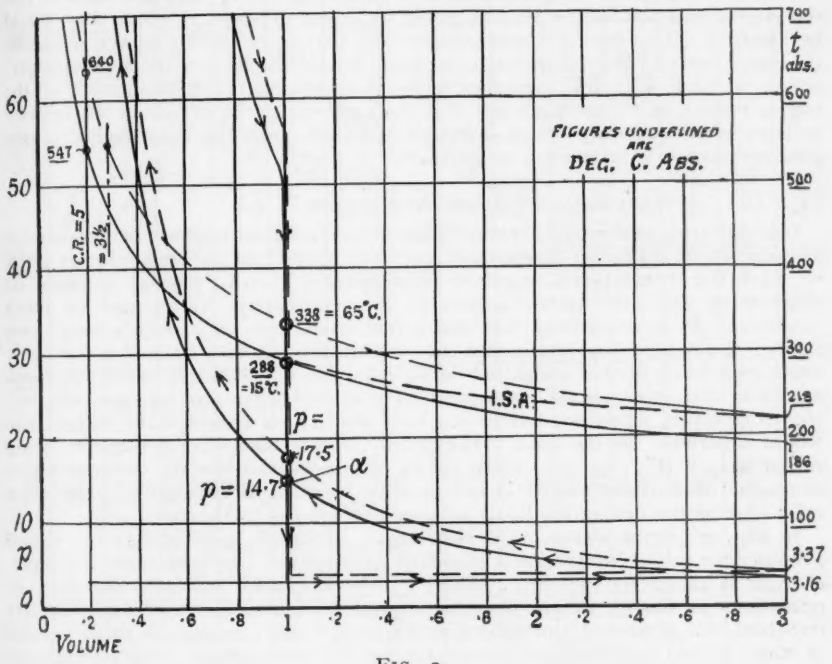

FIG. 9.

Fig. 9 represents the cycle as in a super-compressed engine as a single diagram, the compressor is assumed 100 per cent. efficient. The order of operations is shown by the arrow-heads; when these make a circuit clockwise, as on the left of the ordinate at volume = 1, there is power developed; when the direction is counterclock, as on the right of that line, the power is negative, that is to say, power is absorbed. In reality the negative part of the cycle, to the right of ordinate 1, represents the work done in the compressor. The portion of the diagram on the left of that ordinate represents the cycle of operations actually taking place in the motor cylinder. The graphs given as solid lines represent atmosphere in a state of adiabatic equilibrium; this is the ideal condition; those shown dotted refer to the International Standard Atmosphere. Two pairs of graphs are given, one pair relating to pressure and the other to temperature; figures giving pressures are in italics. The dotted graph marked I.S.A. indicates temperature as related to volume ($1/\rho$) as effected by altitude according to the International Standard. Figures underlined indicate temperatures in the absolute (C.) scale. The volume given 3 (density one-third normal) corresponds to the upper limit of the troposphere. Taking the normal sea-level temperature = 288 on the adiabatic assumption the temperature at volume = 3 would be 186; on the basis of the I.S.A. the temperature would be 218; it will be seen that compressing adiabatically from this temperature the temperature at volume = 1 will have risen to 338. The justification for this mode of representation will be found in Appendix I, Fig. 24.

[8] By convention, sea-level normal temperature and pressure ("N.T.P.") are taken 15°C. = 288 (abs.) and 1.01388 bars (= 760 m.m. mercury reduced to 0°C.) or (British) = 14.7 pounds per sq. inch. Density ρ (c.g.s.) *dry air* = .001226, *saturated air* = .001206, or taken (approx.) = 1/13 = .077lbs./cu.ft.

the cylinder, or cylinders, would be precisely the same at other altitudes as at sea level. Again, if this were true it would mean that whatever the detonation or " knock " limit might be, in view of the nature of the fuel (as gauged by its octane number or otherwise), the compression ratio permissible at sea level would also be permissible at any altitude to which the conditions relate, that is to say, up to the limit of the troposphere.

Under these supposed conditions the power developed by the engine at all altitudes would speed for speed be the same, and if means were provided to test the engine and plot its torque and power curves at different altitudes they would be identical. This does not mean necessarily that the available power would be the same, because provision has to be made for the driving of the supercharger, which, at high altitudes, consumes a by no means negligible proportion of the engine output, but if we postulate that the supercharger is driven by an exhaust turbine, or alternatively by an independent motor, then the consequence of the assumptions we have made is as given.

§15. The " International Standard Atmosphere."

It is unfortunate that the old conception of the lower atmosphere or troposphere as founded on adiabatic equilibrium has been found not to hold. In its place we have the International Standard Atmosphere (" I.S.A.") which is based on observation and atmospheric soundings as representing an average or mean condition. It is recognised that the actual conditions vary over a very wide range;[9] the outstanding fact is that the temperature fall with altitude is less, only about two-thirds of that computed on an adiabatic or isentropic basis. A result of this is that, even on the assumption of a supercharger 100 per cent. efficient, the temperature when boosted to sea level density, is considerably higher than would otherwise be the case. The initial temperature in the cylinder being raised to 338 (Fig. 9), the whole range of temperature during compression is increased; this means that it is not possible to work at as high a compression ratio (due to the detonation limit) as would otherwise be the case.

In Fig. 9 graphs shown solid refer to an isentropic atmosphere; the dotted graphs refer to the International Standard Atmosphere. In both cases the supercharger is taken 100 per cent. efficient. The diagrams represent the cycle of operations as though taking place in a single cylinder, and as from a density one-third that of normal atmosphere at sea level,[10] this corresponds to an altitude of about 35,000 feet, the approximate limit of the troposphere. The co-ordinates represent pressure and volume[11] respectively as in the ordinary indicator diagram. Temperature graphs, also figures indicating the temperature at different points in the cycle, are given.

Fig. 9 (solid lines) shows the temperature as rising from that proper to the density in question, namely, 186 on an adiabatic basis, to reach the normal sea level value = 288 (15°C.) when vol. = 1 (point marked a on the diagram) when also the sea level atmospheric pressure (14.7 pounds per sq. in.) is reached; the index is taken[12] = 1.4. In the graphs shown dotted the initial temperature (as the air is drawn into the supercharger) is that proper to the I.S.A.[13] at 35,000ft., namely, 218 as given in the figure. This results in the temperature being 338 when the charge enters the induction manifold, and as shown, assuming compression ratio = 5, the compression temperature is raised from 547 to 640. If we assume that for the fuel contemplated the temperature of compression when

[9] The relation of temperature to altitude may vary several degrees, representing some thousands of feet for any stated temperature.

[10] In this paper abs. temp. deg. C. are indicated by an underline thus, 288.

[11] Normal value at sea-level taken as unit.

[12] This is the value assumed for the " perfect gas " in place of the value 1.408 commonly given for air.

[13] The International Standard Atmosphere.

at sea level is the limit, then at the altitude under consideration the compression ratio would have to be reduced from 5 to about $3\frac{1}{2}$. The assumption is here made that the maximum compression temperature is the main factor by which the knock limit or highest useful C.R. is defined.[14]

FIG. 10A.

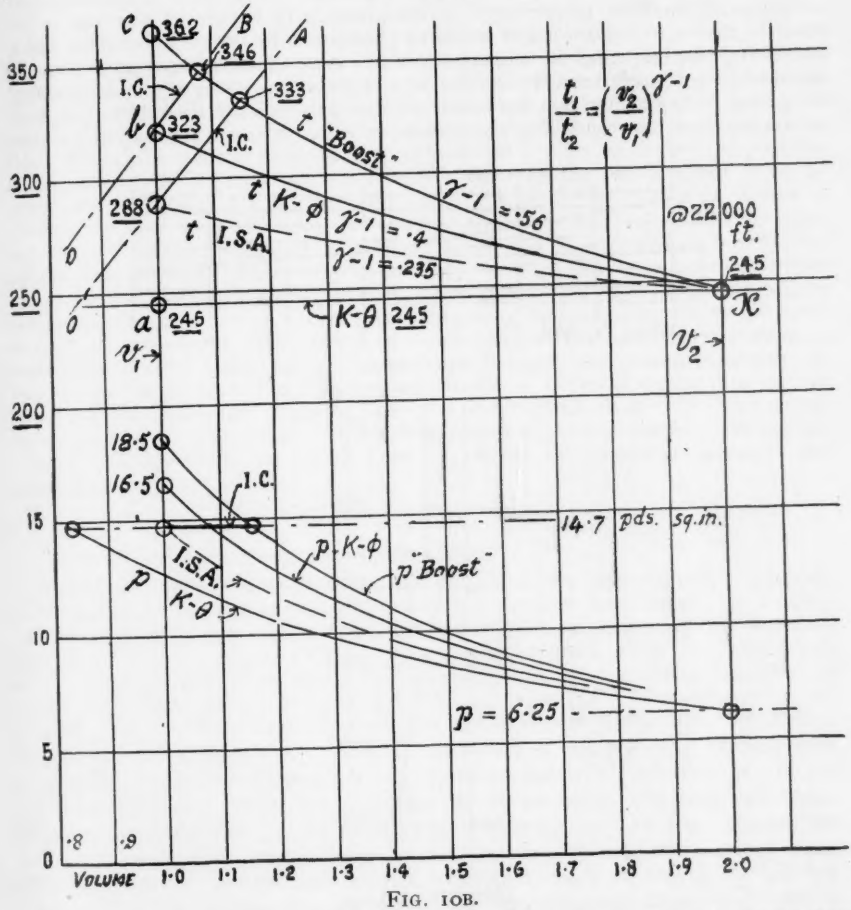

FIG. 10B.

Temperature and pressure graphs indicating the rise in temperature and pressure from altitude datum at 22,000—(1) on an isothermal basis;* (2) on an adiabatic basis;* (3) with "boost"; also graph (shown dotted) representing temperature and pressure as related according to the International Standard Atmosphere. Fig. 10A, incidentally, illustrates the meaning of the term *efficiency* as understood in connection with super-compression ab/ac. Two graphs OA and OB are also given as representing the function of an intercooler. The inclined lines "I.C." relate to intercooling; see text.

[14] Mr. Oliver Thornycroft, writing from Messrs. Ricardo & Co., Shoreham, states that, "The knock limit is also affected by pressure, and there may be differences in the degrees of response to this effect by different fuels. I am afraid this so far has not been fully examined."

* For $K\theta$ read isothermal. For $K\phi$ read isentropic, or adiabatic. Where figures are underlined temperature absolute is understood.

§16. Loss of Efficiency in the Supercharger.

We have as a temporary assumption ignored the loss of power which takes place during the initial compression in the supercharger. This loss can only appear in the form of heat, and when thermal equilibrium is established, this heat must of necessity make its escape with the air (or charge) as delivered to the induction manifold.[15] This results in a considerable increase in the induction temperature, and the temperature of compression is higher in like ratio; the effect of this is to impose a still lower maximum on the compression ratio which (for any given fuel) may be employed. The extent of the temperature increase depends upon what is termed the *efficiency* of the compressor, the understanding being that if the compression were truly adiabatic the efficiency would be reckoned as 100 per cent. corresponding to an increase in temperature from t_1 to t_2; then
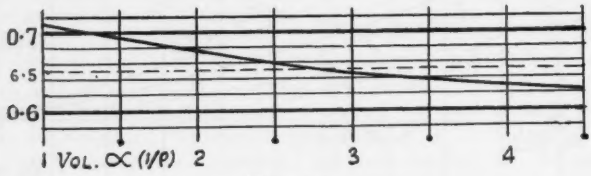
Fig. 11A.

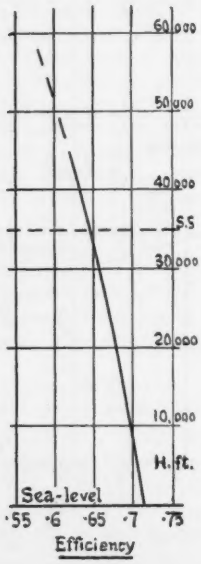

Fig. 11B.

These figures represent respectively the efficiency of a compressor as a function of volume $(1/\rho)$, as derived from the author's expression $P\,V^{1.56}$ = constant, and as a function of altitude.

[15] We are here treating the subject broadly; in the case of a petrol engine the evaporation of the fuel absorbs a part of the heat: in the Diesel this is, of course, not so. Also there is the heat balance to be considered as between loss by radiation and convection from the supercharger casing or exterior, and heat received by conduction from the engine when the two are designed as a combined unit; this cannot be treated generally, it is a matter for the test bench in any individual case.

if the actual increase be from t_1 to t_3 the efficiency will be given by the expression

$$(t_2 - t_1)/(t_3 - t_1)$$

it being understood that the basis is volumetric, *i.e.*, compression from vol. = v_2 to v_1, Fig. 10A. In this figure, in which the ordinates stand for temperature absolute, the efficiency is ab/ac

$$= (323 - 245)/(362 - 245) = 78/117 = 0.67 \text{ or } 67 \text{ per cent.}$$

The author in the present paper has adopted a slightly different basis. Instead of expressing the performance of the supercharger in terms of adiabatic compression as a standard, he has assumed a law of the type pv^n = const. as applicable, in which the index $n = 1.56$ instead of 1.4, which latter applies to adiabatic compression in the case of a perfect gas when no gain or loss of heat takes place; there would seem no reason to adopt a different form of expression in the case of the supercharge compressor. Between the two methods there is, practically speaking, not a vast difference; the author's expression shows a gradually diminishing efficiency (as usually reckoned) with altitude. In Figs. 11A and 11B this is illustrated by two graphs;[16] in Fig. 11A efficiency is plotted against volume ratio (the inverse of density); in Fig. 11B corresponding values are given for altitudes carried up to 45,000ft.; over this range efficiency values fall between 0.62 and 0.71. The author considers that a falling off of efficiency at high altitudes is to be expected, and that the pv^n law is the better form of expression.[17] The index value 1.56 may be thought unnecessarily precise; in view of the variation in the efficiency of blowers of different types, it is certain that no great importance attaches to the second decimal place; the index might for example have been chosen 1.55 or 1.57, with equal justification. When the "boost" *temperature* is to be given in terms of volumetric change, the expression made use of is,

$$t_1/t_2 = (v_2/v_1)^{n-1} \text{ where } n - 1 = 0.56.$$

§17. On Compression Ratio and Temperature.

With further reference to Figs. 10A and 10B, it will be observed that in addition to the graphs *xa* the isothermal; *xb* the adiabatic; and *xc* the "boost" ($n = 1.56$) there is a graph shown dotted, relating to the I.S.A. representing the temperature (Fig. 10A) in which $tv^{0.235}$ = const. and pressure (Fig. 10B) in which $pv^{1.235}$ = const., the index being that corresponding to a uniform reduction of temperature with altitude = (approx.) 2°C. per 1,000ft.[18] The temperature at 22,000ft. may be seen to fall from 288 the sea level standard to 245, the density being half: that is $v_2 = 2\,v_1$. With a compressor of 100 per cent. efficiency the compression from this temperature 245 would be adiabatic, reaching 323 in the induction manifold. With a compressor of 67 per cent. efficiency the boost temperature would rise to 362 as shown. Referring now to Fig. 12, we see that the compression temperatures within the engine cylinder starting from 288 and 362 will, if compression ratio be taken as 8, reach the values 661 and 831 respectively. The former (= 388°C.) is not unreasonably high, and with a suitable fuel might be "knock-free," whereas the latter (= 558°C.) would be altogether excessive, and under these conditions (at 22,000ft. alt.) it would be necessary to adopt a far lower compression ratio. If we base this on a temperature limit, the nearest equivalent on the upper graph is compression ratio = $4\frac{1}{2}$ at which the temperature is 660 = 387°C. In view of the fact that the compression ratio cannot be changed in flight, this would limit it to $4\frac{1}{2}$ with a drop in

[16] No account is taken of the loss of volumetric efficiency which certain types of blower exhibit when slow running, then, over a certain range, the efficiency may rise with altitude.

[17] There is a cumulative effect which should justify the form of expression adopted by the author.

[18] A more exact figure is 1.98.

the theoretical thermal efficiency[19] of from 0.565 to 0.45, a most serious matter. In Fig. 12 are given the temperature values at full compression for compression ratios ranging from 8 down to 3; this enables the temperatures to be compared at these values for the two graphs plotted.

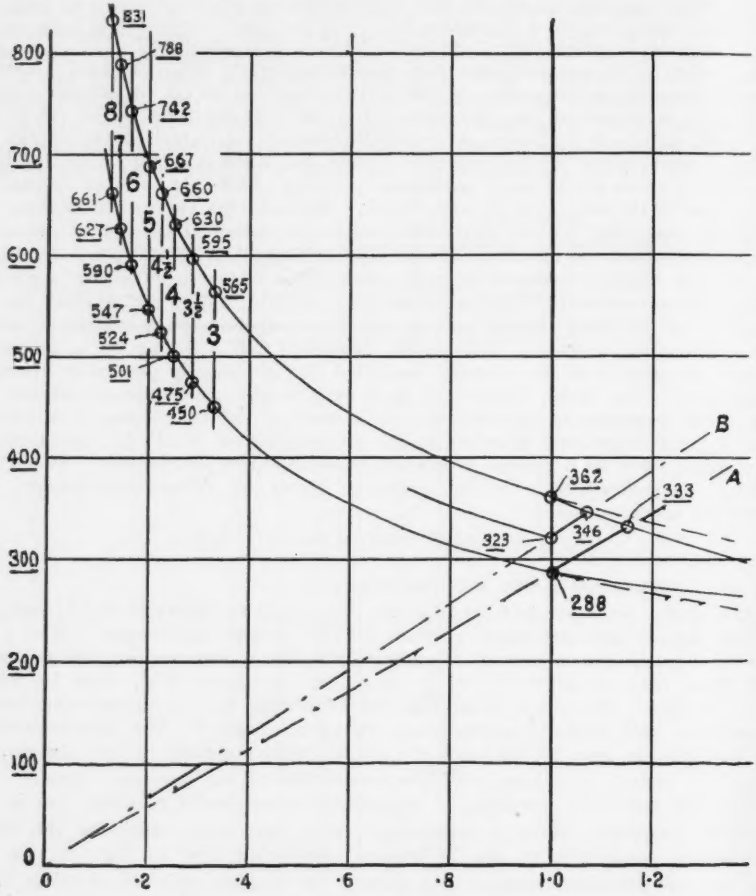

FIG. 12.

This forms a continuation of Fig. 10A giving temperature graphs for cylinder compression starting respectively at normal atmospheric (288) and boost temperature (362). The corresponding temperatures at compression ratios from 3 to 8 (calculated values) are given, enabling a comparison between the two conditions to be made. The graphs relating to intercooling appear in this figure as in Fig. 10A.

The line of treatment adopted in §§16 and 17 above with reference to Figs. 10A, 10B, and 12, is, in its essence, a simplification. When representing the cycle of operations in a super-compressed engine in the form of a *single diagram*, in these figures and in Fig. 9, the whole truth is not disclosed. In the real problem there is more work performed in the supercharger than represented in the diagram, and this additional work is given back in the motor cylinder, this is

[19] At all altitudes, see Fig. 19.

incidental to the *transfer* of the charge. The net result is the same so far as the development of power is concerned, except that a certain loss is incurred in the said transfer. The justification for the author's " simplification " is established in Appendix I hereto.

§18. INTER-COOLING.

It is doubtless owing to the considerations discussed in the preceding section that the subject of cooling the charge after boost, before entering the engine cylinder, has been receiving serious consideration of late. The position as disclosed in Fig. 12 is far too serious to be accepted as satisfactory, and the only solution seems to be a certain measure of inter-cooling. A thermodynamic interpretation of this is given in Figs. 10A, 10B, and Fig. 12. It will be seen that when the boost pressure becomes equal to that of normal atmosphere (Fig. 10B), the temperature will have reached the value 333 (Fig. 10A), then maintaining the pressure constant if the charge be passed through an inter-cooler till vol. $= v_1$ the temperature will also have reached normal, namely, 288 (15°C.). This is made clear in Fig. 12, in which it will be seen that the cooling graph is a straight line directed to the origin or zero o, namely, volume and temperature fall in like ratio, pressure being constant. The diagrams as drawn refer specifically to 22,000ft. altitude. Could this full measure of inter-cooling be effected the difficulty would be disposed of for all altitudes (up to the stratosphere), the compression graph would, within the cylinder, be the same under all conditions, namely, the lower of the two depicted in Fig. 12. There appears to be some doubt whether the inter-cooling should be carried to the point of bringing the charge to normal temperature as suggested above. It has been suggested that there might be some condensation of the heavier fractions of the fuel under such conditions. This would probably be true if the theoretical temperatures given were likely to be reached in practice, but just as we know that " spray pipe " or manifold temperatures are always in excess of normal, so we might infer that, in the interpretation of the régime given, the temperature nominally = 288 or 15°C. would be actually more nearly in the region of 300° (27°C.) and other temperatures proportionally higher. However, it is of interest to consider a rather less ambitious proposal, let it be laid down that the inter-cooling provided shall reinstate the condition of 100 per cent. boost efficiency, that is to say, we bring the temperature down to that which would be reached at vol. $= v_1$ starting adiabatically from the air temperature at 22,000ft., namely, 245. The temperature graph for this adiabatic is given in Fig. 10A and at vol. $= v_1$ the temperature is 323. Laying out the cooling graph (line OB) its point of intersection with the boost graph gives temperature = 346, this being the temperature at which the charge enters the inter-cooler. On this basis the inter-cooling may be regarded as merely making amends for the loss of efficiency in the boost. On the previous basis so long as the power required to drive the compressor is derived without putting a tax on the engine output, the ideal condition is fulfilled, namely, for given revolution speed the torque and power will be capable of being maintained up to the limit for which the supercharge system and the inter-cooler have been designed; this at least is true up to 35,000ft. alt., at which level the stratosphere is entered. Above that limit a rather greater measure of cooling will be necessary, that is all.

§19. THE ENGINE AT ALTITUDE.

Fig. 13A represents a typical torque curve as ascertained, and Fig. 13B the corresponding h.p. graph. The maximum h.p. of which the engine is capable as shown corresponds to a point on the torque curve tangent to a hyperbola *hh* at which point torque × r.p.m. is maximum. Under our ideal conditions when

the charge enters the manifold at sea level temperature and pressure, the torque curve will be unaffected by altitude, up to the limit for which full supercharge provision has been made; thus referring to Fig. 14, in which abscissæ represent torque and ordinates altitude, the engine torque corresponding to maximum h.p. will be represented by a vertical line up to the limit in question, the " knee,"

FIG. 13A.

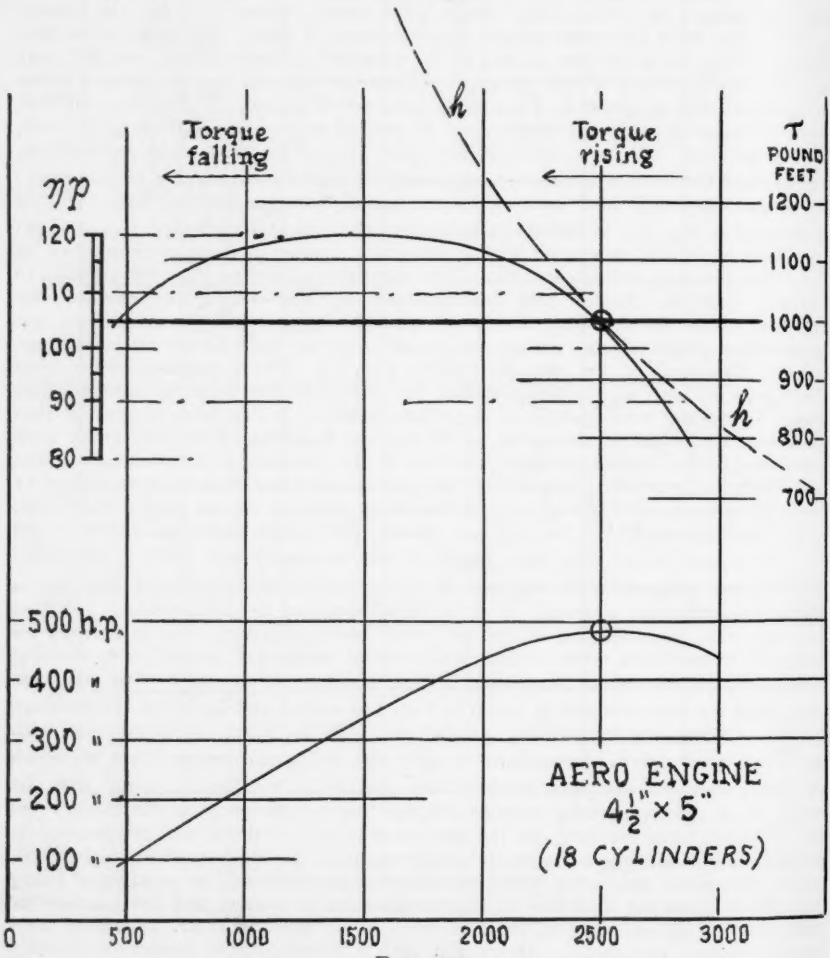

FIG. 13B.

Torque and h.p. graphs relating to hypothetical aero engine, 480 maximum h.p.

after which it will fall off approximately as the density, this is as shown in the figure, it will be understood that when an engine is without supercharge the " knee " does not appear, it is at sea level (graph " O ") other graphs are given showing the limit of torque at primary ceiling levels = 10,000, 20,000, and 30,000ft. respectively.

If we assume the " boost " to be given without inter-cooling, the induction temperature will rise as a function of altitude, if we assume this to take place in accordance with the graph $\overline{xc}$ in Fig. 10A the total mass of the charge will be unaffected, and were it not for the " knock " limit we might regard the engine torque as still remaining constant. But under real conditions either the compression ratio has to be lowered (as a matter of design) or a weaker mixture must be administered. In the former case the torque, owing to the lower thermal efficiency, will undergo a reduction at all altitudes, or in the latter there will be a falling off of torque as the altitude becomes greater, depending upon the degree of attenuation of the mixture strength found necessary.

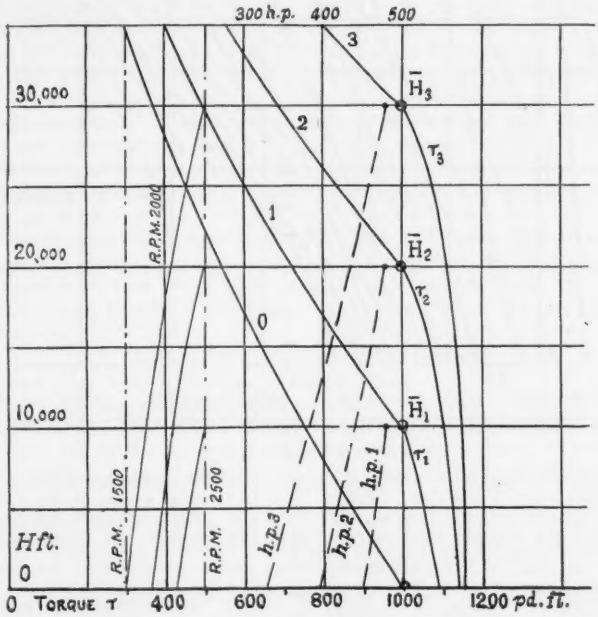

FIG. 14.

Figure representing torque and h.p. for ceiling levels $\overline{H}$ = 10,000, 20,000 and 30,000ft. Based on the assumption that the aeroplane is flown under optimum conditions, up to the ceiling height given and that the engine is that whose characteristics are specified in Figs. 13A and 13B, developing its maximum power (478 h.p.) at the ceiling level; that is to say, the speed of revolution (given in graphs on the left-hand of the figure) is in each case 2,500 r.p.m. These graphs are based on the understanding that the effective pitch of the propeller is constant, so that the r.p.m. is proportional to the optimum flight velocity as defined by a K-span graph. It will be observed that in every case the torque graphs indicate a value higher than at $\overline{H}$ for all lower altitudes; this corresponds to the fact that the optimum velocity is less at all lower altitudes and in accordance with Fig. 13A the torque is higher than at maximum h.p. The graphs as drawn accord strictly with Fig. 13A. The three graphs h.p. 1, h.p. 2 and h.p. 3, correspond to the three torque graphs and correspond to Fig. 13B. The torque graphs given above the $\overline{H}$ levels are based on the law that torque varies as density; they have no other signification. The actual torque must depend upon the r.p.m. (as in Fig. 13A) and this is an unknown quantity when, as is the case above the ceiling, the machine can no longer be flown under optimum conditions. Likewise the h.p. under such conditions is indeterminate. Also when a variable pitch propeller is employed the diagram no longer applies, the relation between r.p.m. and flight velocity no longer holds, even as an approximation. The lower scale relates to torque (graphs shown solid), the upper scale relates to h.p. (graphs dotted). The scale relating to the r.p.m. graphs is clearly indicated. See also text.

§20. Engine Power and $\bar{H}$.

Now it is the maximum h.p. as determined with reference to Figs. 13A and 13B (or as modified by the conditions discussed) that determines the K-power graph in the chart, Fig. 8, here reproduced from Part I, and the maximum

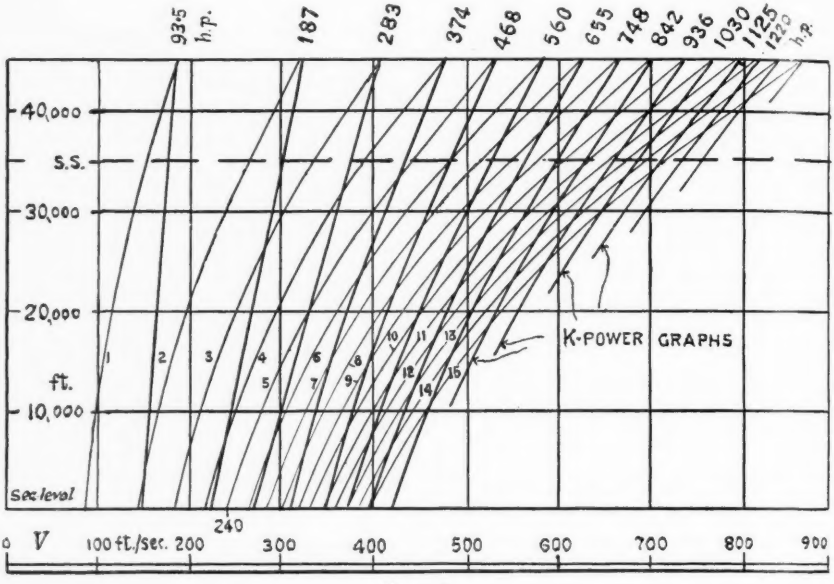

Fig. 8.

Fig. 8 above is brought forward from Part I. In this figure the cartesian co-ordinates give H the altitude and V the flight velocity. The network of graphs define S the span and P the power. This chart, which is an epitome of the main conclusions reached in Part I, is fundamentally the starting point on which the discussion of the power plant is based. See also caption relating to this figure in Part I.

altitude or primary ceiling $\bar{H}$ is that for which full supercharge provision has been made, the " knee " in Fig. 14. These two together give a definite point on the chart, and the two remaining variables are thus determined, namely, the K-span graph giving the correct span, and the flight velocity at ceiling level. Moreover, the K-span graph read in relation to the velocity scale gives the optimum flight velocity at all lower altitudes. If, on the other hand, we have to deal with a machine " in being " whose span is therefore known, the intersection of the K-power graph and the K-span graph in question gives the value of $\bar{H}$, the primary ceiling height (the " knee " in Fig. 14), for which provision must be made in the design and proportioning of the supercharger. As before, the flight velocity at this ceiling is read off on the velocity scale. Again, if the machine " in being " is required to have a definite ceiling, and the problem is that of making the necessary power provision, the point of intersection on the chart of the desired ceiling level and the K-span graph will enable the appropriate h.p. to be specified, by interpolation between the two nearest K-power graphs.

The author has met with diagrams similar in appearance to Fig. 14, in which abscissæ are stated to represent h.p. instead of torque; he finds the interpretation of these diagrams difficult in view of the fact that no specific guidance as to the speed of revolution is given. If a constant r.p.m. is presumed then it would be better to specify torque as such; if this is not so, there must be some under-

standing on the subject of the speed of revolution in relation to altitude which needs elucidation. In particular there is a form of graph sometimes given in which from sea level up to the " knee " the h.p. is showing a steady increase of a character similar to those given in Fig. 14, but nothing is said as to whether this increase is associated with an increase of torque or due to an increase in the r.p.m. or whether it is due to both in combination. Also, it does not seem clear whether or not the particular form of graph in question (or other form given) is determined by the idiosyncrasies of some one or other particular type of charger.[20]

§21. Engine Torque and Power in Relation to Altitude.

In a diagram such as Fig. 14 it is possible to be quite definite (within the ordinary degree of approximation) for altitudes below the primary ceiling, if we assume, (*a*) that the machine, of which the engine forms a part, is being flown under optimum conditions, that is to say, its flight velocity in relation to altitude is defined by a *K*-span graph; and, (*b*) if we assume the propeller to be of constant effective pitch. These two conditions allow us to assert that the engine revolutions are in constant relation to the flight velocity. On this understanding the revolution speed (relating to the typical engine, Figs. 13A and 13B) has been plotted (to the left of Fig. 14) and based on this the h.p. is given (h.p. graphs, h.p. 1, h.p. 2, etc.).

In accordance with the *K*-span graph the r.p.m. of the engine is at all altitudes less than at the primary ceiling; the torque (as shown by Fig. 13A) is greater, we are thus able to plot the torque graphs up to ceiling level τ_1, τ_2, and τ_3 as given.[21] The h.p. graphs may either be derived from the torque graphs so plotted, thus:—

$$\text{h.p.} = (2\pi \text{ torque} \times \text{r.p.m.})/33{,}000$$

or direct from Fig. 13B, it makes no difference.

It may be noted that the conditions below the primary ceiling do not result in velocities so low as to involve a falling torque (as to the left hand of Fig. 13A), at least this is so in the typical example given. It could only be otherwise if the primary ceiling were high up in the stratosphere, in the region of 45,000ft. altitude.

When we come to deal with the state above the level of the primary ceiling, the conditions become extremely complex. It may be said that once we desert the *K*-span graph (which represents the optimum condition) we find ourselves in the same position as a train that has gone off the rails, the subsequent eventualities depend upon circumstances which we cannot altogether control or predict. Firstly, be it remarked that the flight velocity will have become less than optimum, and the resistance, no longer constant, will depend upon considerations discussed in Part I with reference to Figs. 3 to 6. Secondly, no definite law connects flight speed with altitude, or engine revolutions with flight speed, so that it is impossible to establish a relation between h.p. and altitude even were

[20] A group of such graphs is shown in a paper by E. W. Stedman as relating to different types of supercharge mechanism. The Engineering Journal, Aero. Section Report, December, 1936, p. 21.

[21] This increased torque is available for climbing. If the condition of horizontal flight alone were in question the engine would not be called upon to develop more torque than that at ceiling level, namely, 1,000 pound ft., actually this climbing condition would, to some extent (depending upon the propeller characteristics), affect the relation between r.p.m. and flight velocity, and so in some degree invalidate the argument; it would, in effect, be an infringement of condition (b) above, *i.e.*, the *effective* pitch of the propeller would be no longer constant. In the light of the above the actual torque will be somewhat less than given by the graphs, τ_1, τ_2 and τ_3, for, when, without an actual change of pitch, the *effective* pitch becomes less, the consequent increase of engine speed tends to diminish the torque without material change in the torque thrust relation. When, on the contrary, at low altitudes the engine gains speed from an actual reduction in the propeller pitch, the thrust in relation to torque may be greatly increased.

the engine torque assumed at some average value. In Fig. 14 all that the author has been able to do is to give graphs 0, 1, 2, and 3, representing the relative torque as proportional to the density (a function of altitude). These may be construed as the torque at 2,500 r.p.m., namely, that of maximum h.p. according to the graph 13A. But equally any other r.p.m. might be chosen with the corresponding torque, and the graph would be one technically parallel to that given, but this would not be consistent with the value at primary ceiling altitude as given. Actually what we do not know is in what manner r.p.m. and torque vary after leaving the primary ceiling level; the author considers this to be indeterminate unless based upon some convention or assumption for which at present he can find no clue or justification.

Those who think the question is merely one of the performance of an engine under variable conditions of temperature and density (as due to altitude) without regard to the aeroplane—the whole machine—of which it forms a part, are fundamentally in the wrong.

§22. Concerning the Propeller.

Whilst flying at the ceiling or any less altitude under optimum conditions as determined by the K-span graph we have learned that the resistance is constant; and the propeller being of constant pitch the engine torque necessary to horizontal flight will also be constant, that is, in Fig. 13A it will be defined by the horizontal line $\tau = 1{,}000$ pd. ft. This torque graph at lower speeds indicates the torque margin and consequently the thrust margin available for climbing. When maintaining the velocity at optimum value the propeller is called upon to provide thrust for climbing as well as for horizontal flight, and the slipstream velocity will be proportionally increased; this will mean that the revolution speed will be greater whilst climbing than for horizontal flight, and it will be greater in relation to the flight velocity. This will have a certain influence as affecting the interpretation of Fig. 13A. If on a *rising*[22] torque curve, the margin of torque will be somewhat reduced. If the revolution speed be such that the torque curve is (locally) horizontal, the margin of torque will not be affected. If it should happen to be at a still lower speed where the torque is falling,[23] then the increase of propeller speed will be beneficial as resulting in an increase of torque.

These facts, although worthy of mention, do not materially affect the main issue.

§23. The Case for Variable Pitch.

With a propeller of constant pitch, at velocities less than that proper to ceiling altitude, the engine will be running at speeds below that of maximum output. It is obvious that the performance at low speeds, and when taking-off, may be improved by the adoption of a propeller of variable pitch. Thus, in other words, at low altitudes the pitch requires to be reduced in order to allow the engine to "get away" so that its full power may be developed. For many years the production of an aeronautical propeller of varying pitch remained a problem unsolved, but the difficulties have now been overcome.

The case for the variable pitch propeller is not always presented in this exact form, that is to say, it is not always looked upon as *a standard propeller of which the pitch may be reduced*, but however regarded it comes to the same thing in the end.

§24. Above the Ceiling.

This may seem a contradiction in terms, but it has been explained that the primary ceiling $\overline{H}$ as defined is not an absolute altitude limit. Assuming a

[22] As defined in Fig. 13A.

[23] This is the region of the torque curve at which, when in testing with a prony brake, the running becomes unstable and the engine stalls.

definite " knee " at which a break away from the condition h.p. = const. gives place to the relation *torque varies as density*, we may begin with the case of an engine destitute of supercharger, in which the " knee " does not appear on the diagram; it is at sea level (graph o, Fig. 14). Then, making comparison with the same engine supercharged to constant induction temperature and density, the figure shows the " knee " as at various altitudes.

The form of the graph in Figs. 13A and 13B could be ascertained experimentally as affected by density or pressure by testing an engine in a low pressure chamber, but for most purposes it is sufficient to assume that for a given engine the type of torque graph is the same, and that the magnitude of the torque and the power developed are proportional to the density or nearly so. A mere question of a change in the ordinate scale.

At the knee in Fig. 14 (which defines $\overline{H}$ the primary ceiling) the whole of the available h.p. is required and expended in flight. Below the knee the full h.p. is still available, but whether or not it can be fully developed depends upon the propeller pitch being adapted to the flight velocity, as already explained. The question remains: What happens above the " knee "? Firstly, it may be observed that the value of $\rho^{\frac{1}{2}}V$ must fall, that is the machine will no longer be flown at so high a velocity as that to which its span relates. Secondly, so long as an increase of height is possible, a departure from optimum conditions does not necessarily involve an actual reduction of flight speed as is true at constant altitude, but rather a falling away from the K-span graph, which defines the optimum condition. It is obvious from Fig. 8 that this is not inconsistent up to a certain point with an actual increase in flight velocity.

§25. Surface Heat Transference.

In relation to the present subject this may be paraphrased as *surface cooling*. Many years ago the author from purely physical considerations was led to the conclusion that it should be possible to establish a definite connection between skin-friction and the rate of cooling when a current of air passes tangentially over a heated surface. This theory may be found outlined in a memorandum dated March, 1913, in the Reports of the Advisory Committee for Aeronautics.[24] In an addendum to this memorandum the late Dr. T. E. Stanton pointed out that a similar conclusion had been reached by Osborne Reynolds in a paper on the heating surface of boilers published in 1874; in this addendum he gave the argument as presented in Osborne Reynolds' paper, which is in strict mathematical form, and showed that the result is identical with the expression given in R. & M. 94 above cited.

The author's conclusion was based on the following considerations. There is identity between the dimensions of viscosity and thermal conductivity[25] and, whenever a transference of momentum takes place within the fluid, as due to surface drag, there will likewise be a transference of heat *pari passu*; hence, if we calculate the mass of air, which, *brought to the state of motion of the surface*, would account for the observed resistance, then the heat transfer may be assessed on the basis of that same mass of air being *brought to the temperature of the surface*.[26]

In a paper, entitled[27] " The Cylinder Cooling of Automobile Engines," read

[24] R. & M. 94, 1912-13, p. 40. The practical application of this theory antidates this by many years.

[25] According to the author's version of thermal dimensions, which is widely (but not universally) accepted.

[26] This ignores the heat transference which would take place at zero velocity as due purely to conduction. This proves to be negligible in the case of air, but not so when water is concerned.

[27] Proceedings, Institution of Automobile Engineers, Vol. X, p. 59, 1915. In this paper, p. 82, the expression $V^3/10^8$ is given as the h.p. expended per sq. ft. in overcoming skin-friction, representing the *theoretical minimum* work done in cooling. The expression from which this is derived is $\mathbf{C}_0\rho V^3/32.2\times550$, it would seem that in this case $\mathbf{C}_0$ was taken = .0023.

by the author in 1915, the expression for heat loss per sq. ft. of surface is given in the form—

$$\text{h.p. equivalent} = V\theta/15{,}000 \text{ (otherwise} = 0.0000666\ V\theta) \quad . \quad (1)$$

where θ is the temperature difference in degrees Fah., and V velocity in ft./sec. The equivalent of this, if θ be expressed in deg. C., is

$$\text{h.p.} = V\theta/8{,}330 = 0.00012\ V\theta \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The derivation of this expression is as follows. Skin-frictional drag per sq. ft. $= \mathbf{C}_o\rho V^2$ poundals. Then if (m/s) be a hypothetical mass, lbs. per second, to which is imparted the full velocity V, we have[28]

$$(m/s)\ V = \mathbf{C}_o\rho V^2 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

or

$$(m/s) = \mathbf{C}_o\rho V \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Let θ = temperature difference in deg. C., and 0.24 being the specific heat (k_p) for air,

$$\text{C.H.U. per sec.} = 0.24\,(m/s)\,\theta = 0.24\ \mathbf{C}_o\rho V\theta \quad . \quad . \quad (5)$$

or ft. pounds/sec.[29] $= 1{,}400 \times 0.24\ \mathbf{C}_o\rho V\theta = 336\ \mathbf{C}_o\rho V\theta$,

$$\text{h.p. equivalent}[30] \text{ (per sq. ft.)} = 336\ \mathbf{C}_o\rho V\theta/550 = 0.61\ \mathbf{C}_o\rho V\theta \quad . \quad (6)$$

Then at sea level where $\rho = 0.077$,

$$\text{C.H.U. per sec. (per sq. ft.)} = 0.0185\ \mathbf{C}_o V\theta \quad . \quad . \quad . \quad (7)$$

or

$$\text{h.p. equivalent (per sq. ft.)} = 0.047\ \mathbf{C}_o V\theta \quad . \quad . \quad . \quad (8)$$

In the author's early notation skin-friction was given by a "double surface" coefficient ξ indication the drag of a material flat plate in edgewise presentation, in terms of its resistance in normal presentation, so that $\mathbf{C}_o = \xi\,(0.6/2)$ in which 0.6 is the normal plane drag constant. Then ξ being taken $= 0.0085$[31] we have $\mathbf{C}_o = 0.00255$, and, by (8) above,

$$\text{h.p. equivalent (per sq. ft.)} = 0.00255 \times 0.047\ V\theta = 0.00012\ V\theta,$$

as given above, (2).

§26. Surface Cooling. Applications.

The theory when first formulated related primarily to the motor road vehicle, and was found to be fairly reliable in that connection, where the Reynolds number $\mathbf{N}_R$ was in the region of 2×10^5. Thus the linear parameter, the thickness of a honeycomb radiator block, from front to back, taken as 0.4ft., with V about 60 to 70 ft./sec. gave $\mathbf{N}_R = 2 \times 10^5$ as stated.[32] Referring this to the skin-friction chart, Fig. 15 (an excerpt from Fig. 2 of an earlier paper),[33] it will be seen that this value is consistent with a graph defining $\mathbf{C}_o$ extending from value 0.003 where $\mathbf{N}_R = 10^5$ to 0.002 where $\mathbf{N}_R = 10^6$. This lies about midway between the graphs F_2 and F_1, being William Froude's values for a well varnished surface and one tinfoil coated respectively.

For most purposes as concerns cooling problems met with in connection with aircraft, the motor vehicles of other kinds, the value of $\mathbf{N}_R$ lies between the limits 10^5 and 10^6 covered by Figs. 15 and 16,[34] assuming, as extreme cases, a motor car whose radiator block measures 0.33ft. (front to back) at 50 ft./sec. giving $\mathbf{N}_R = 10^5$, and an aeroplane (at sea level), say, $L = 0.5$ft. and

[28] C.f. Journal Royal Aeronautical Society, February, 1937, p. 76.

[29] 1. C.H.U. = 1400 ft.pounds.

[30] It is usually convenient to express the heat per second in terms of its mechanical equivalent in h.p. because the heat rejected is commonly expressed as a proportion of the engine output.

[31] Justified by data at that time available.

[32] We did not use the term Reynolds number in those days.

[33] "The Part Played by Skin-Friction in Aeronautics," Royal Aeronautical Society Journal, February, 1937.

[34] In Fig. 16 a uniform linear scale has been adopted.

V = 320 ft./sec. (220 m.p.h.) when $\mathbf{N}_R = 10^6$. Although a case may be made out for making use of the values of $\mathbf{C}_o$ given in Figs. 15 and 16, the author makes use of 0.0025 as representing the average conditions.[35]

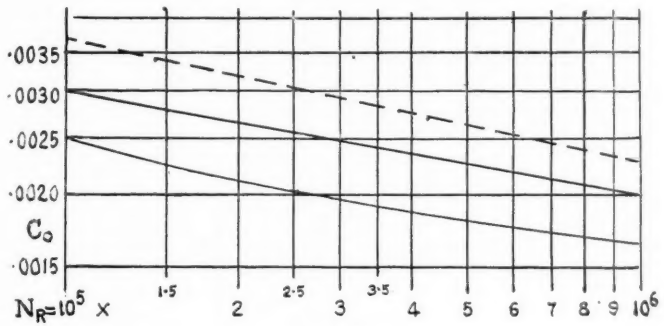

FIG. 15.

A logarithmic diagram giving $\mathbf{C}_o$ values as a function of $\mathbf{N}_R$. The lowest of the three graphs is a prolongation of a graph F_1 founded on Froude's determinations for a tinfoil-coated surface. The upper graph (shown dotted) is as given by Wieselsberger's equation and may be taken as a prolongation of F_2, namely, Froude's determination for a varnished surface. These graphs are taken from Fig. 2 of the author's previous paper (Journal, R.Ae.S., Feb., 1937, p. 68). An intermediate graph is shown which is that referred to in the text.

§27. REFERRING TO THE BOUNDARY LAYER.

A great deal has been said on the subject of the laminar condition of flow and the " boundary layer." The author can see no reason to discuss the question of laminar flow in the present connection except to say that it is a condition to be, as far as possible, avoided. In practice this requires no special effort. In a so-called " radiator " of the honeycomb type (which is that giving the smoothest possible passage to the air stream), at the entering edge where the tubes are united (by soft solder), a certain amount of thickness (bluffness of " entry ") is inevitable, certainly sufficient to initiate the turbulent condition of flow at the outset. It would, in the author's opinion, be a mistake to make any effort to

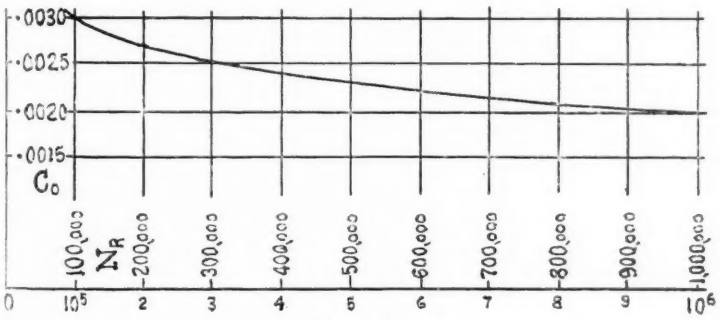

FIG. 16.

The graph here given is identical with the intermediate graph in Fig. 15, plotted in the ordinary way to a uniform scale.

[35] This is approximately identical with the value assumed in his I.A.E. paper, C.f. §26. It is doubtful whether it is of advantage to attempt to secure a low value of $\mathbf{C}_o$ when dealing with the problem of cooling. Probably the reverse is the case.

avoid this; he believes that the turbulent condition is one to be encouraged, and that the cooling may even be enhanced by artificial turbulence, although to this there must be some limit.

§28. Engine Cooling.

That it is necessary to provide means for the removal of waste heat from the cylinder of an internal combustion engine is so well known as to need no comment; it is to be regarded as an unfortunate necessity. The two methods of cylinder cooling,[36] commonly known as air-cooling and water-cooling, are more correctly to be described as *direct* and *indirect* cooling, since in both the ultimate dispersal of heat takes place through an air-swept surface. In direct cooling the temperature is limited only by the degree of heat which the combustion space and cylinder walls will stand without giving trouble; on the other hand, the surface area is strictly limited to that which it is possible to apply direct to the cylinder in the form of a gilled jacket. In indirect cooling, that is to say, when a liquid in circulation intervenes between the cylinders and the air-cooled surface, the area of the latter exposed to the air stream may be made anything the designer may please, but the surface temperature is limited by the boiling point of the liquid used, and in this connection allowance has to be made for the reduction of pressure and lowering of the boiling point at altitude. This contrast in the conditions results in there being two distinct problems which need individual consideration.

§29. Direct Air-Cooling.

For the purpose of initial comparison the two systems may be contrasted as at sea level. In a paper on cylinder cooling, to which reference has already been made,[37] the author took 140°C. as a safe mean surface temperature for the gills of an air-cooled cylinder; to-day it is probable that the limit may be taken considerably higher, say, at 165°C. If we accept this we have for normal temperature = 15°C. the temperature difference = 150°C. For reasons which will be more fully explained later it is not possible to utilise the whole of this difference, the air passing through the " jacket " has its temperature considerably increased and instead of 15°C. (its temperature of entry) we must take a higher value. If we allow the emergent air as showing an increase of 20°, the mean may be taken = 10°, then the mean temperature difference 150°-10° = 140°C. which is the θ of our equation. Next we have to consider the amount of heat for the dispersal of which provision must be made. We will take for the purpose of illustration the hypothetical engine specified in Figs. 13A and 13B having a maximum b.h.p. = 480.

Now, under the conditions of air-cooling, it is sufficient to allow 0.6 of the power output as the equivalent of the jacket heat,[38] that is, heat equivalent = 290 h.p. Taking $\mathbf{C}_o$ = 0.0025, and velocity V = 200ft. sec.

$$\text{h.p. per sq. ft.} = 0.61 \times 0.0025 \times 0.077 \times 200 \times 135 = 3.15.$$

Or surface area required = 290/3.15 = 90 sq. ft. The engine being specified as of 18 cylinders this gives 5 sq. ft. per cylinder. The extent of cylinder wall and head may be taken as 0.75 sq. ft. which given a surface factor[39] = 5/0.75 = 6.6.

[36] Cooling by the boiling away of water (as in some of the earliest motor cars) is, of course, out of the question, as is also the direct cooling by water as applied in marine vessels and launches.

[37] Proceedings, Institution of Automobile Engineers, Vol. X, p. 59, 1915.

[38] In a water-cooled engine it may be taken equivalent = 2/3 b.h.p. Compare " The Flying Machine from an Engineering Standpoint," footnote p. 63. " From tests made by the author, in the case of a Daimler (sleeve valve) engine 39.2 b.h.p., total jacket heat rejected = equivalent of 40 h.p. or cylinder and head only (not including exhaust port loss) equivalent = 27 h.p." In an air-cooled engine a greater proportion of the heat loss is carried off by the lubricant and by conduction to the crank case

[39] The fins, on this basis, pitched $\frac{1}{4}$in. apart would be $\frac{3}{4}$in. in height.

This may be deemed satisfactory. The heat emission from all parts of the cylinder head and wall is not uniform; the density of heat flow (the rate per sq. inch of wall) is far higher in the head, in the neighbourhood of the exhaust, than elsewhere.[40] Fortunately a correspondingly greater temperature difference in that region is permissible.

§30. Indirect Cooling.

We are only concerned here with the radiator. The temperature difference available will depend not only on the liquid employed as the intermediary, but also on the boiling point as affected by altitude.[41] For the present purpose a maximum temperature 85°C. will be assumed giving a temperature difference $\theta = 70$°C. Then

$$\text{h.p. per sq. ft.} = 61 \times 0.0025 \times 0.077 \times 200 \times 70 = 1.65.$$

In an indirect or " water " cooled engine a greater proportion of the waste heat commonly passes into the jacket than when the cooling is direct. It is fair to take the proportion as two-thirds or in the present case 320 h.p. Hence the area of surface necessary will be

$$320/1.65 \text{ or, say, } 200 \text{ sq. ft.}$$

In such radiators the " frontage " area is commonly about 1/60th of that of the air-swept surface, so that the radiator block would have a frontage 3.3 sq. ft. with tubes (if of the honeycomb type) of length about 15 diameters. The radiator indicated will thus be not greatly different in size or proportion to that of a high powered motor road vehicle. The greater the length of the tubes in terms of diameter, the greater the increase in the temperature of the air stream and the *less the effective temperature difference*. To avoid this there must be a *plethora* of cooling air.

If we take a different basis of calculation this is made manifest. At 200 ft. sec. the mass of air passing through 3.3ft. area $= 3.3 \times 0.077 \times 200 = 50$lbs. per sec., or C.H.U. per sec. per deg. $= 0.24 \times 50 = 12$. The heat to be removed per sec. (equivalent to 320 h.p.) $= 126$ C.H.U. Hence the air stream will undergo increase temperature $= 126/12 = 10$°C. or mean increase $= 5$°C. This implies that in order to maintain the value of $\theta = 70°$ the maximum surface temperature must be increased from 85° to 90°C.

If greater depth were assigned to the radiator block (longer tubes) the frontage area for a given surface would be less; consequently the mass of air passing per second would be reduced, and the temperature difference correspondingly greater.

The relation of ground level to high altitude conditions as affecting the efficiency of the cooling system is dealt with in a later section with reference to Fig. 18.

§31. Cooling as Related to Altitude.

We make it a proviso that the aeroplane is flown at all altitudes under optimum conditions, that is to say, at a velocity defined by a K-span graph. Then $V\sqrt{\rho}$ is constant, or equation (6) may be written

$$\text{h.p. equivalent} = 0.61\ \mathbf{C}_0\rho^{\frac{1}{2}}\theta \times \text{const.}$$

the constant being $V\rho^{\frac{1}{2}}$ as above.

A graph for $\rho^{\frac{1}{2}}$ is given in Fig. 17, in which also the value of $\mathbf{N}_R$ is plotted on the basis of data given. Corresponding values of $\mathbf{C}_0$ taken from Fig. 16 are figured in the right-hand margin.

This leaves only the temperature difference $\theta\ (= t_2 - t_1)$ to be determined from the conditions as ascertained or assumed.

[40] Where the surface temperature is frequently > 300°C.

[41] Although at the moment our calculation relates to sea-level, that is not supposed to be the ceiling.

Application.—We will make the computation at three altitudes, *i.e.*, sea level, 20,000ft. and 35,000ft. Thus, from Fig. 17,

	Sea level.	20,000ft.	35,000ft.
$\sqrt{\rho}$ =	0.278	0.200	0.155

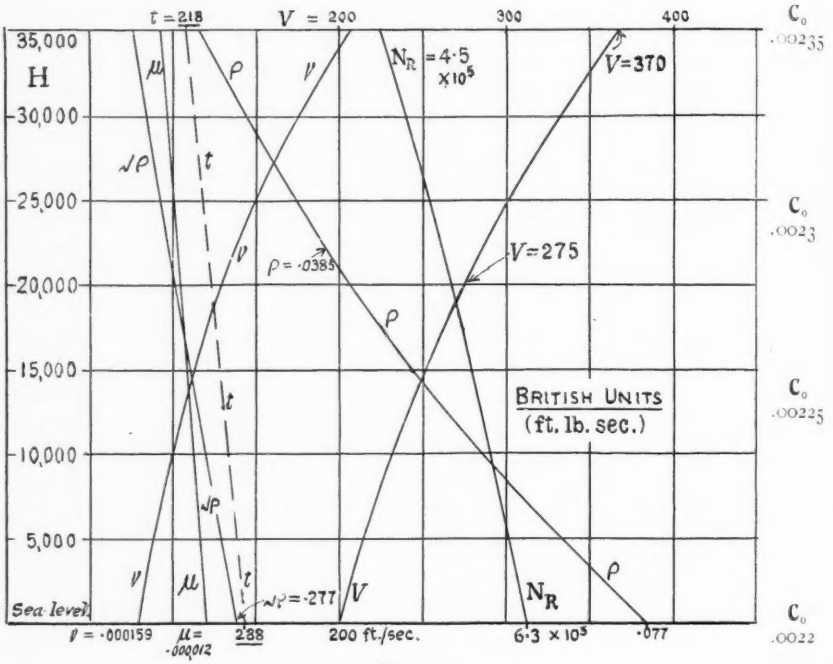

FIG. 17.

In this figure will be found plotted as a function of altitude, atmospheric density ρ, temperature t, viscosity μ, kinematic viscosity ν, $\sqrt{\rho}$, and velocity V. A graph for N_R is given founded on appropriate data as related to the cooling surface.

As stated in §26 the variations in the value of C_0 given in Fig. 15 and 16 are not worth taking into account in view of the many uncertainties otherwise present. The value 0.0025 will be generally assumed, as justified by the conditions.[42]

§32. COOLING (*continued*). THE ENGINE AT ALTITUDE.

In §§27, 28 and 29, the subject of engine cooling was dealt with as at sea level. In §30 the influence of altitude has been discussed and a simplified expression given which relates to variations of altitude under optimum conditions for an aeroplane of given weight and span; that is to say, the expression is limited in its application to conditions corresponding to some particular K-span graph.

In Table I different values of temperature, t_2 given in cols. 1 and 2 are assumed by way of example as relating to the cooling surfaces. In col. 3 temperatures t_1 are given relating to the temperature of the air stream as determined by altitude, and in col. 4 is given the temperature difference, namely, $t_2 - t_1$. In col. 5 a deduction of 10 per cent. has been made on account of the temperature of the

[42] The surfaces are not always conformable to the flow and are not usually polished or highly finished.

air stream having been raised in its passage.[43] This allowance represents a lowering of the mean temperature difference. The figures so derived are taken as the temperature difference θ in the equation.

TABLE I.

	1	2	3	4	5	6	7
Altitude	t_2 C.	t_2 abs.	t_1 abs.	$t_2 - t_1$ C.	Less 10% $= \theta$	$\sqrt{\rho}$	$x\ \theta/12$ h.p. sq. ft.
At sea level	70	343	288	55	50	0.28	1.17
20,000ft. ...	,,	,,	248	95	85	0.20	1.42
35,000ft. ...	,,	,,	218	125	113	0.15	1.42
At sea level	100	373	288	85	77	0.28	1.8
20,000ft. ...	,,	,,	248	125	113	0.20	1.88
35,000ft. ...	,,	,,	218	155	140	0.15	1.75
At sea level	140	413	288	125	113	0.28	2.63
20,000ft. ...	,,	,,	248	165	150	0.20	2.50
35,000ft. ...	,,	,,	218	195	175	0.15	2.20
At sea level	180	453	288	165	150	0.28	3.50
20,000ft. ...	,,	,,	248	205	185	0.20	3.10
35,000ft. ...	,,	,,	218	235	212	0.15	2.65

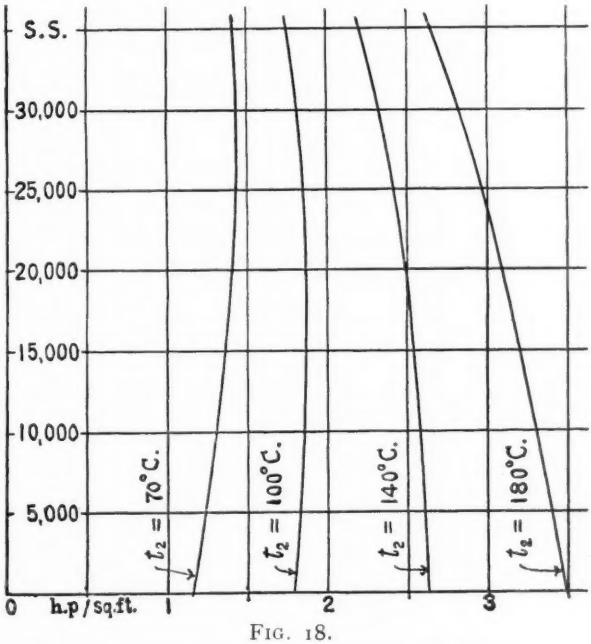

FIG. 18.

Four graphs relating to surface temperatures showing the relative efficiency of cooling at low and high altitudes.

[43] It would clearly be wrong to take $t_2 - t_1$ as the temperature difference, because however great the plethora of air passing the hot surface its temperature must be raised to some extent. In practice the extent of the increase would be either measured or calculated for any particular case as demonstrated in §29. Here it is only possible to suggest a correction in general terms.

By way of illustration the case is taken of an aeroplane whose optimum velocity at ground level is 200 ft./sec. giving for the constant of the K-span graph $V\rho^{\frac{1}{4}} = 200 \times 0.278 = 55$.

Taking as in §30 $\mathbf{C}_o = 0.0025$, the simplified expression there given $= 0.61\ \mathbf{C}_o\rho^{\frac{1}{4}}\theta \times 55$ resolves itself into $0.084\ \rho^{\frac{1}{4}}\theta$ or for slide-rule convenience $\rho^{\frac{1}{4}}\theta/12$. This is made use of in Table I, cols. 6 and 7. The results have been plotted in Fig. 18 for the values of surface temperature given. The approximate constancy of the cooling rate over a considerable range of altitude is without doubt due to the fact that the falling off which would be expected on account of the lower density is set off against an improvement due to higher flight speed and to the greater temperature difference at high altitude for any given value of the surface temperature T.

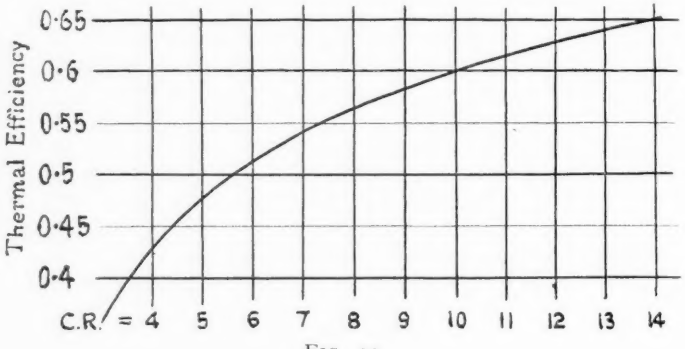

FIG. 19.

Graph giving thermal efficiency (theoretical) as a function of compression ratio.

With a propeller of fixed pitch, the engine at low altitudes is running slower than at high altitudes, and the jacket heat to be disposed of is less. If, however, a variable pitch propeller be adopted, so that the engine may develop its full power at low altitude, the conditions are fairly represented by the graphs as plotted.

§33. ON THE INTER-COOLER. THE PROBLEM OF HEAT TRANSFERENCE.

The heat to be absorbed by the inter-cooler is easily ascertained. We may take as basis 1lb. air passing per second; this is substantially the quantity of air required for our hypothetical engine of 480 h.p., the graphs for which are given in Figs. 13A and 13B. The change of temperature takes place at constant pressure (see Fig. 10B), hence sp. heat = 0.24.

Assuming an altitude 22,000ft. (ρ = half normal), with full inter-cooling (line OA, Fig. 12) the temperature reduction is $\frac{333}{} - \frac{288}{}$, namely,

$$45°\text{C. or C.H.U.} = 0.24 \times 45 = 10.8$$

$$\text{h.p. equivalent} = 10.8 \times 1{,}400/550 = 27.5.$$

The temperature difference between surface and air stream, at the altitude in question will vary from $\frac{333}{} - \frac{245}{} = 88°$C. where the air charge enters the cooler, to $\frac{288}{} - \frac{245}{} = 43°$C., where it passes to the induction manifold. This assumes that there is a plethora of cooling air, such that its rise of temperature during interchange may be neglected. We will register a 10 per cent. reduction as an allowance on this account, and strike a mean giving 60°C. In the case of an inter-cooler there are two surface transferences of heat to share this difference so that the temperature difference, the θ of our equation, may be taken as 30°C.

Assuming $\mathbf{C}_0 = 0.0025$, as given in the preceding section, and $V = 275$ (see Fig. 17),

$$\text{h.p. per sq. ft.} = 0.61\ \mathbf{C}_0\rho^{\frac{1}{2}}\theta \times \text{const.}$$

The value of the constant $= V\rho^{\frac{1}{2}} = 55$,

$$\text{h.p. sq. ft.}^{44} = 55 \times 0.61 \times 0.0025 \times 0.2 \times 30 = 0.5.$$

($\rho^{\frac{1}{2}}$ at 22,000ft. $= 0.2$).

Or area required $= 27.5/0.5 = 55$ sq. ft.

If we suppose the surface to be provided by tubes of aluminium alloy whose walls are 0.008 inch thick, this will represent a weight for the actual cooling surface = 9lbs. The weight of an inter-cooler complete with inlet and outlet conduits and connections on this basis would probably be not less than 20 or 25lbs. As such it will represent an addition of about 0.05lb. per h.p. to the power plant.

If we take a lesser degree of inter-cooling as suggested by the line OB in Figs. 10A and 12, the temperature difference $= 346 - 323 = 23$°C., and the equivalent of the heat to be disposed of for one lb. air per sec. will be

$$0.24 \times 23 \times 1{,}400/550 = 14 \text{ h.p.}$$

The temperature difference between surface and air stream will vary from $346 - 245 = 101$°C. to $323 - 245 = 78$°C. After 10 per cent. allowance as before the mean value is 80°C. or (allowing for double heat transference) $\theta = 40$°C.

$$\text{h.p. per sq. ft.} = 55 \times 0.61 \times 0.0025 \times 0.2 \times 40$$
$$= 0.084 \times 0.2 \times 40 = 0.67.$$
$$\text{Surface required} = 14/0.67 = 21 \text{ sq. ft.}$$

The weight addition will be proportionately less than in the previous example.

In an inter-cooler such as that under discussion, whereas a plethora of wind with very free passages is necessary in order to promote efficiency, the counterpart passages through which the air charge passes needs to be, comparatively speaking, restricted.

Appendix I.

It is stated in the text, §17, that the discussion of the supercharge cycle has been based on a convention; a simplification of the conditions as concerns the relation of the supercharger to the engine proper. No account has been taken of the fact that when a compressed charge passes into the cylinder it does work on the piston, and this is additional to the work performed as shown by a normal indicator diagram. This additional work is furnished by the supercharger and requires that additional power be supplied to drive the supercharger than would be the case under the simplified régime. This may be otherwise expressed by saying that a certain amount of energy is circulated; the supercharger does work on the engine, and in turn the engine has to reimburse the supercharger. The conditions will now be more closely examined.

To make the point clear, in Fig. 20 it is suggested that a system is employed, in which a charge taken into the " pump " cylinder B is transferred by way of an induction valve to the motor cylinder A, then during initial compression the pressure in cylinders A and B is the same, and the work done in the motor cylinder by the pump (compressor) will be represented by a graph p_1 and that done in the pump cylinder will be represented by the graph p_2, abscissæ representing volume; it is the area (shaded) represented by the graph p_1 which is added to the energy performed in the working cycle of the motor cylinder, and which has been furnished by the work done in the pump cylinder. This is an idealised form of supercompression, the real conditions will next be taken.

The boost pressure from a compressor is virtually constant, that is due to the fact that a blower of whatever type has a more or less constant rate of delivery, and an aero multi-cylinder engine a fairly constant rate of acceptance. The

[44] Or $= 0.2 \times 30/12 = 0.5$ (C.f. §31).

conditions are similar to those which would prevail in the case of a single cylinder engine by the interposition of a reservoir or pressure vessel between the compressor and the induction valve. When the latter opens, air is allowed to rush into the cylinder, and so will immediately raise the products of combustion to boost pressure. Then, during induction this boost pressure performs work on the motor piston throughout the stroke, Fig. 21, so that in the net performance of work in the motor cylinder the boost pressure is added to the mean indicated pressure. The transfer of energy from the supercharger to the motor cylinder

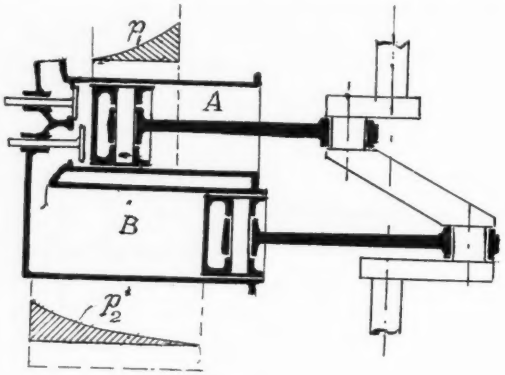

FIG. 20.

Illustrating the cycle of operation of a supercharger under ideal conditions. *Diagrammatic*. The volumetric ratio as drawn is 2:1.

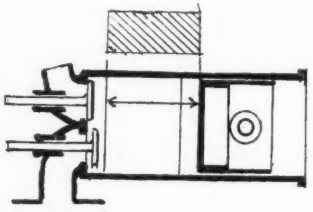

FIG. 21.

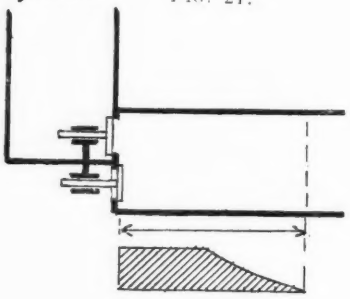

FIG. 22.

Fig. 21 illustrates the condition of constant boost pressure, as approximately that which obtains in practice: in contrast to that shown in Fig. 20. Figs. 21 and 22 taken together illustrate diagrammatically super-compression as in a single-cylinder engine, with intermediate pressure reservoir. The volumetric ratio as shown is 2:1.

in this case, Fig. 21, is greater than in the previous example, Fig. 20. The volumetric ratio in both cases, as represented, is 2 : 1.

In order to allow of the conditions being studied more closely the problem of supercharge applied to a single cylinder engine will be next considered.

The simplest disposition will be to include a pressure reservoir in the system, Fig. 22, which will provide a cushion between the compressor delivery and the motor cylinder. We postulate this as of sufficient capacity to make pressure fluctuations negligible.

Now we are assuming that the charge density is brought to the value as at sea level, so that the loss of power due to induction (" wire-drawing ") will be the same as at sea level, whatever may be the altitude. This is the *transfer loss* and therefore has not to be taken into account when considering the efficiency of the supercharger.[45] In Fig. 22 the compressor is shown diagrammatically as

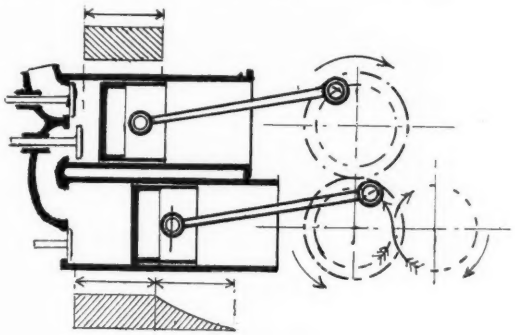

FIG. 23.

A study in super-compression for a single-cylinder engine based on a purely hypothetical mechanism, intended to show as separate the two phases, namely, compression and transfer of charge.

of the piston type and its duty is complete when it has delivered its charge to the reservoir; its efficiency is thus related to the *act of compression*, and is not concerned with transfer losses. This is a justification for the author's convention as embodied in the simplified treatment given in the text.

A modified régime as applicable to the single cylinder engine is represented in Fig. 23, and one which is still more definite in its implication. This is based on the conception of a special mechanism to drive a piston compressor in such manner as to separate the functions of compression and transfer. To effect this (on paper!) we postulate that the path of the connecting rod head is a figure of 8, as represented, so that each stroke of the compressor piston will consist of two equal harmonic motions. These on the out-stroke draw in the new charge, whilst the motor piston is compressing the previous charge and ignition and expansion are taking place. Then the first half of the return stroke of the pump piston is devoted to the initial compression of the new charge, whilst in the motor the exhaust stroke is taking place. Then the induction valve opens, and during the second half of the pump return stroke transfer takes place, this synchronising with the suction stroke of the motor piston, the pressure during transfer is thus constant.[46]

In Fig. 23, as before, for the purpose of illustration, the boost compression ratio (volumetric) is represented as 2 : 1. It is clear that the work performed by the compressor during transfer is precisely equal to that imparted to the piston

[45] In Fig. 22 there would be a transfer loss between the compressor cylinder and the pressure reservoir which would not exist under actual conditions and may therefore be ignored.

[46] The author has not thought fit on the present occasion to take into account the influence of combustion space volume as absorbing part of the compressed charge.

during the same period. The only loss is that due to the portage restriction, which, as already pointed out, does not come into the account when discussing supercharger efficiency.

In Fig. 24 the complete cycle is represented corresponding to Fig. 9 in the text. Here the volumetric ratio is 3 : 1, as in Fig. 9. The upper diagram A and open arrow heads refer to the cycle as performed in the motor cylinder; in

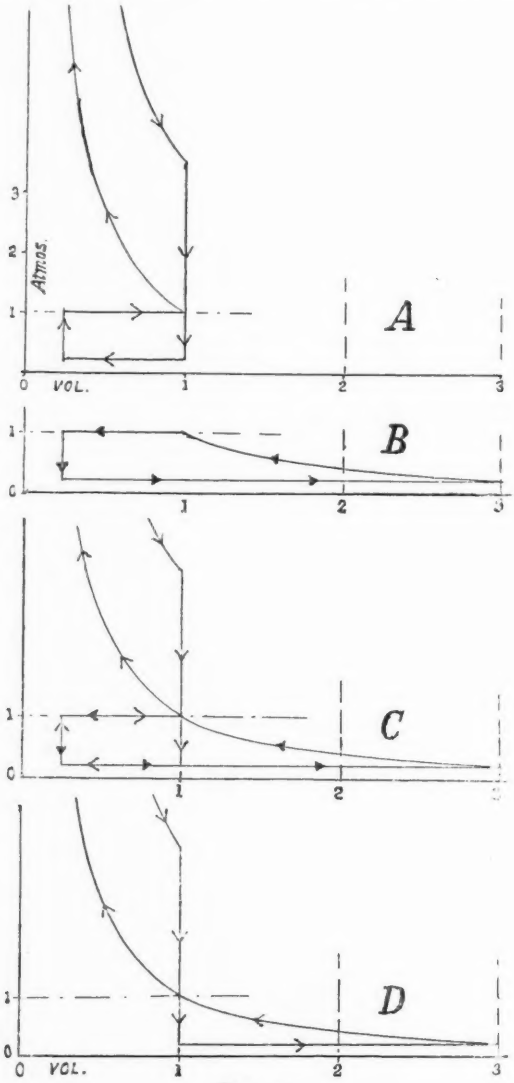

FIG. 24.

Representing the separate and combined cycles of operation as taking place, A in the motor cylinder, B in the compressor, and C in combination. The resultant D is given as justifying the simplified representation illustrated in Fig. 9 of the text. Volumetric ratio = 3 : 1.

diagram B the solid or black arrow heads relate to the corresponding cycle in the compressor. When the directions indicated by the arrows describe a closed curve round an area *clockwise* work is being performed. When, on the other hand, the direction is *counter-clock* work is being absorbed; in other words, the work done is negative. It will be seen by reference to Fig. 24c that the complete diagram consists of three loops, the main (upper) loop, which is only part shown, and which is the usual indicator diagram, familiar to us all, denoting by its area work done. The lower loop (to the right hand of the diagram) in which the arrow direction is counter-clock, represents work done by the compressor. The remaining loop, rectangular in form, is traversed in both directions, those in the clockwise direction denoting work performed in the motor cylinder, and those counter-clock representing work derived from the compressor. These being equal and opposite cancel out, and may be omitted, as in Fig. 24D and in the figures given in the text. This is the basis of the simplification adopted and its justification.

There are occasions when the complete diagram as in Fig. 24, A, B and C, has to be considered, as for example when prescribing the supercharger driving mechanism; this must be " man enough " to take charge of the whole area to which the blacked-in arrow heads relate, including efficiency losses.

Appendix II.

The relations of fuel as gauged by the octane number (or other test of similar character) and detonation, is far too complex to permit of the highest useful C.R. for an engine of novel design being forecast with any approach to certainty. The work of Mr. H. R. Ricardo[47] is generally accepted as quite reliable so far as it goes. In the diagram, Fig. 25, the solid graph R (here reproduced by kind permission of Mr. Ricardo), the relation of highest useful C.R. to octane number in the same engine is presented as applying to a single cylinder experimental engine in which the C.R. was made variable.[48] This particular engine was of the poppet valve type, with two exhaust and two inlet valves, the cylinder and head being water-cooled.

Many influences are at work which render it unsafe to apply any such data to engines generally. Besides the influence of compression ratio (which is mainly a matter of compression temperature) the temperature of the cylinder head, especially as concerns " hot spots " has a great influence. It is usually stated that the sleeve valve engine being comparatively free from " hot spots " has an advantage which may be expressed as equal to a difference of about one in the compression ratio, this in the region C.R. = 6 or 7. In the poppet valve engine the exhaust valve and the region adjacent thereto is where the local temperature is highest; but the position of the sparking plug has a considerable influence. It will take a very extensive (and expensive) research, covering a wide field if the designer is to be put in a position to predict (for any particular fuel) the highest useful C.R. in advance; at present he can only do so if he sticks closely to previous practice, of which he is already in possession of test bench data. Whether such an extended research will ever be undertaken may be considered doubtful; there is a growing tendency to abandon petrol and go over to the self-ignition type of engine. This tendency will receive added impetus as the distances flown become greater, and fuel weight becomes relatively more important in comparison with dead weight of engine.

When considering the influence of compression ratio on detonation it is not definitely known whether the whole effect is due to temperature or whether it may in part be due to pressure, and if so, in what degree. It is believed that, for given temperature, pressure has some influence and tends to promote knock. It is, of course, well understood that mixture strength is a very important factor.

[47] Messrs. Ricardo & Co. (1927), Limited, Bridge Works, Shoreham-by-Sea, Sussex.

[48] The author finds that this graph may be expressed very closely by an empirical equation. C.R. = $(3.5 \times \eta^3) + 4.5$, in which η is the proportion of iso-octane. Thus if $\eta = 0.9$, C.R. = $(3.5 \times 0.729) + 4.5 = 7.05$ as given by graph. See caption.

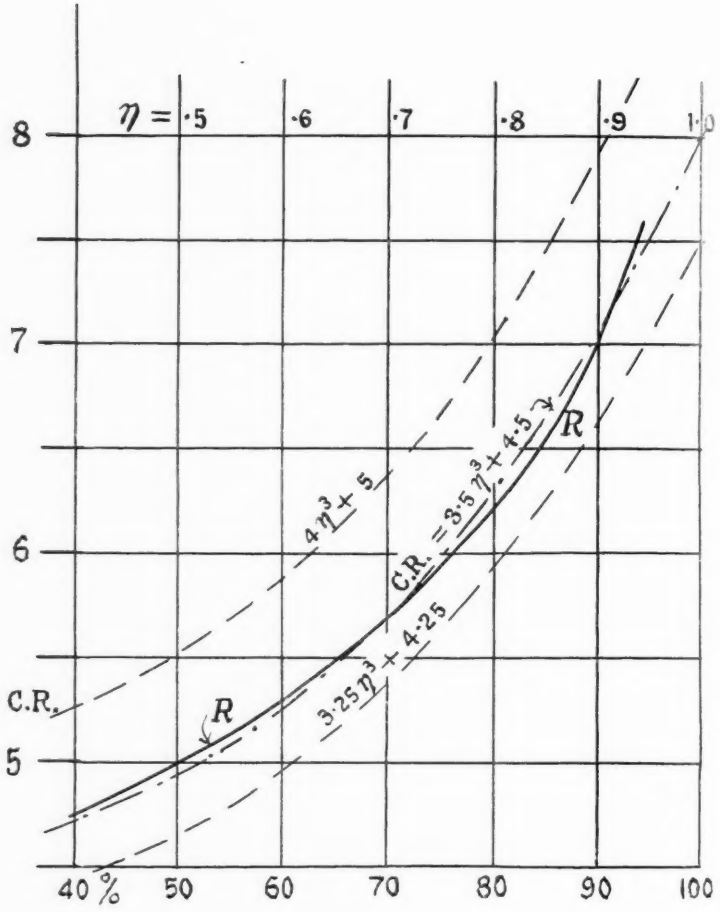

FIG. 25.

Relation between octane number and highest useful C.R. (Ricardo). Poppet valve engine "E.35," 4¾in. dia. × 8in. stroke. *Conditions*:—Compression variable. 1,500 r.p.m. Water cooled, outlet temperature 60°C. Induction temperature artificially maintained; 1,350 watts with room temperature 20°C. Wattage varied according to variations in room temperature.

Mixture strength adjusted to give maximum detonation.

Ignition adjusted for maximum power.

Abscissæ give percentage volume of iso-octane in heptane.

Ordinates give highest useful compression ratio.

The solid graph marked *R* is as given by Messrs. Ricardo. The other graphs shown are based on an empirical equation (proposed by the author) of the form C.R. = $(\eta^3 \times m) + n$, in which η = proportion of iso-octane. Taking $m = 3.5$ and $n = 4.5$ the graph (shown as a chain line) is a close approximation to the graph *R*. The upper graph (dotted), in which $m = 4$ and $n = 5$, may be taken to represent the conditions in a sleeve valve engine. The lower graph (dotted), in which $m = 3.25$ and $n = 4.25$, is an attempt to indicate what might be expected in the case of a combustion space of inferior design, as say that shown in Fig. 27.

These added graphs are mere suggestions. If extrapolated down to zero octane number the value of n would in each case represent the limiting compression ratio.

Strengthening or weakening the mixture on each side of that of "complete combustion," both tend to inhibit detonation. The scope on the weak side is small and of no practical importance in a petrol engine.[49] On the rich side, however, detonation may be suppressed to an extent which enables the power of a petrol engine to be increased above its normal capacity on a fuel of given quality.[50]

As concerns the shape of the combustion space and the position of the sparking plug, a comparison of Figs. 26 and 27 is illuminating.[51] Messrs. Ricardo attribute the superiority of the head illustrated in Fig. 26 to its compact form

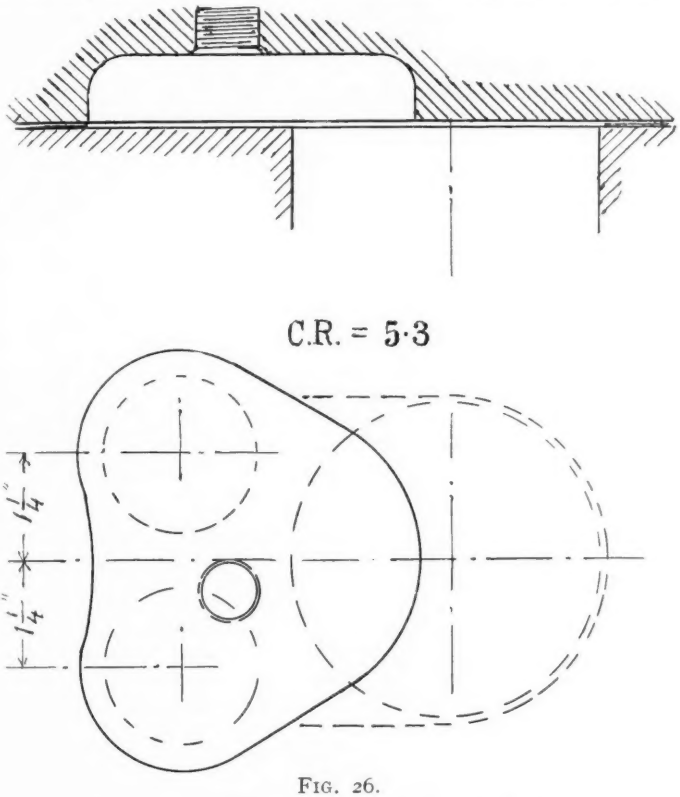

FIG. 26.

and to the fact that the ignition plug occupies a central position, the idea being that the flame has nowhere far to travel and so there is less opportunity of the development of an explosive wave such as is admittedly the prime cause of knock. They also express the opinion that turbulence is of importance as tending to diffuse heat which otherwise might be localised and give rise to a local high temperature. With these views the author finds himself partly in agreement.[52] Turbulence is undoubtedly important both as tending to "de-localise" exhaust valve heat and as neutralising the Hopkinson effect. But another point arises. When combustion proceeds along an ever narrowing passage it is clear that the

[49] It is a different matter if the fuel be rich in free hydrogen.
[50] The author makes this statement on the authority of Messrs. Ricardo.
[51] With acknowledgments to Messrs. Ricardo.
[52] The distance the flame has to travel cannot in itself be accepted as an explanation because if this were so in a large engine it would be almost impossible to get rid of knock. For this reason the author is not entirely satisfied with the explanation given.

wave front energy must become concentrated in an ever diminishing mass of charge and this has a tendency to initiate a detonation wave just as in the case of a tidal wave passing up an estuary may give rise to a " bore."[53] The form of the combustion space in Fig. 27 lends support to this view.

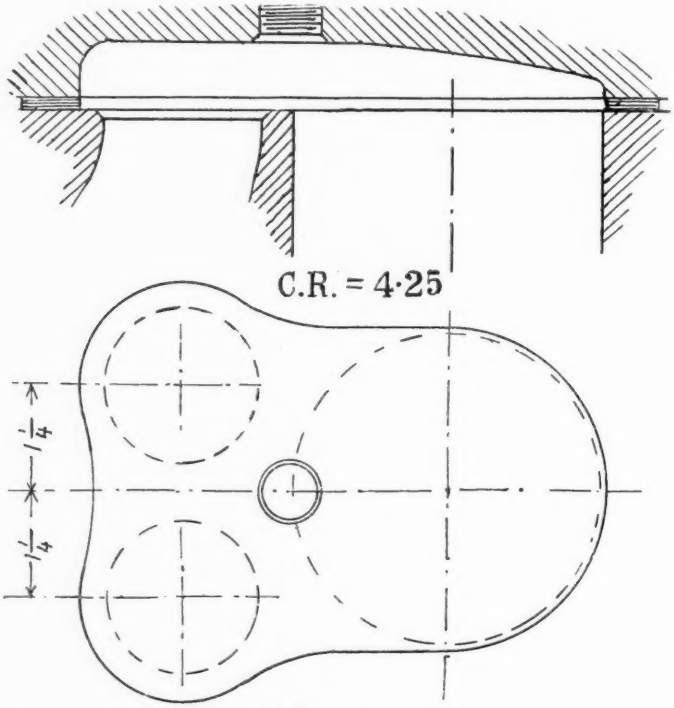

FIG. 27.

Figs. 26 and 27 show in contrast the results of tests on two designs of head in which the same fuel is used, and in which the conditions are otherwise identical. In Fig. 26, the highest useful C.R. is 5.3; in Fig. 27 it is 4.25 (Ricardo).

Some 40-45 years ago, when the author was connected with the design and manufacture of gas engines, we attributed " knock " to the fact that when the flame reached the last portion of the mixture, the compression pressure had risen to very nearly the peak pressure of the explosion and that the knock was due to spontaneous ignition. This view is still held in some quarters and in all probability it is a contributory cause.

Although such simple explanations may have some weight, it is not to be expected that a full explanation will ever be given without going far deeper into the thermal physics and chemistry of combustion. Much has been done in this direction already, it has been shown that combustion takes place in definite stages and, to express it colloquially, the explosive wave which is a characteristic of detonation, has its origin in the " back areas." Certain experiments suggest that it is started by some secondary reaction behind the wave front proper and passes through this in its more rapid advance, just as in a military assault a second wave of infantry may be thrown forward when the first has spent its force. We can only hope for a final solution of this extraordinarily complex problem as a result of the close co-operation of the chemist, the physicist, and the engineer. That, at least, is the author's belief.

[53] The River Severn is a famous example.

MONOCOQUE CONSTRUCTION.*

By I. J. GERARD, M.Sc., Assoc.M.Inst.C.E., *Associate Fellow.*

(Lecture read before Five Branches of the Society and the Students' Section.)

The general idea of making aircraft of single-shell or monocoque construction is not new. In the middle ages, the great English philosopher and man of science, Roger Bacon, "conceived of a large hollow globe made of very thin metal and filled with ethereal air or liquid fire, which would float on the atmosphere like a ship on water," and ever since the inception of the aeroplane, suggestions have been made to construct aircraft wings and fuselages in the form of shells like those of crabs, lobsters or other popular crustacea.

There is at present, a marked trend in aeroplane construction towards the increasing use of metal covering both for wings and fuselages. The water loads on the hulls and floats of various aircraft have always necessitated the use of a robust skin, and although at first wood was commonly used, this was at an early stage of development, replaced by metal.

One of the chief attractions of making aircraft components in monocoque construction is the utilisation of the skin, which determines the form of the component, for carrying stress. It is, on the other hand, inadvisable to count on a contribution from the fabric covering when estimating the strength and stiffness of a frame structure covered with fabric.

Another attraction of monocoque construction is the concentration of structural material towards the outer surfaces, which results in maximum internal space, free from obstructions, for the accommodation of crew, passengers, freight, engines, fuel and other tanks, instruments, etc. This may give considerable help in reducing frontal area, and therefore total drag, to a minimum.

The importance of saving weight and of reducing overall drag in an aeroplane makes it economically possible to carry refinement in design to a point not usually attempted in any other form of structure. For example, in a commercial aeroplane it is estimated that 1 per cent. saving in weight may yield a 4 per cent. reduction in cost of transport, and an apparently small reduction in drag may also yield a substantial financial economy especially for high speed aircraft.

The attainment of this ideal of single shell or pure monocoque construction would necessitate the use of some light material, which, in shell form, would sustain all necessary tensile, shear and compressive loads. In general, it may be said that a flat sheet will support a tensile stress in proportion to the tensile strength of the material and regardless of the thickness of the sheet. Its capacity, however, to carry shear and compressive stress is dependent on the ratio of thickness of the sheet to length and breadth of unsupported surface. Instability failures by waving and buckling of the sheet will intervene at comparatively low apparent shear or compressive stresses in all but compact structures incorporating relatively thick shells. If the strength of all materials of construction were strictly proportional to their density, we should, therefore, choose a material of such a low density as to give us sufficient wall thickness to ensure stability under all requisite shear and compressive loads.

On this basis, wood, say in the form of plywood, may in some cases be preferable to metal as a material for the shell and a light alloy may be preferable to steel.

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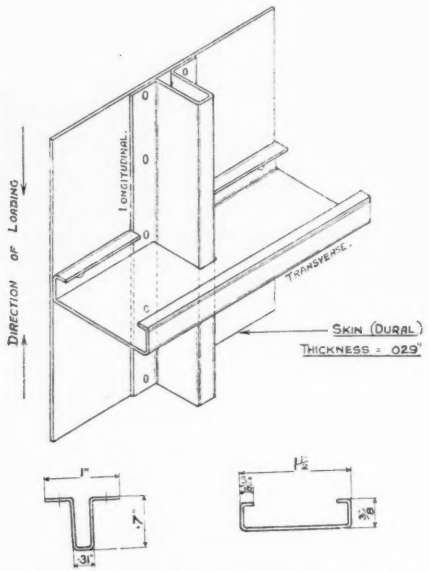
Owing to the limitations of available materials, however, a more practical construction than the pure monocoque for all but comparatively small aircraft, is a hybrid construction comprising skin reinforced by internal stiffeners capable of taking compressive loads. This type of construction is sometimes called semi-monocoque construction, and for light spread-out structures it is in many cases more efficient than the pure monocoque construction on a strength/weight basis, as the design utilises both the efficiency of the skin in taking tensile loads and the efficiency of the stiffeners in taking compressive loads. The skin in turn may also be utilised to support the stiffeners in such a way as to enhance their capacity for carrying compressive loads.

It appears, therefore, that the design of a light and efficient semi-monocoque construction requires minimum practical thickness of skin, reinforced by internal stiffeners against collapse by waving or buckling due to compressive and/or shear loads. The design of the stiffeners covers a wide field of types and is analogous to the design of spars and struts. Fortunately, there already exists a useful accumulation of data to enable us to design efficient tension joints in thin sheet and also efficient struts and spars. There are also data to enable us to estimate what compressive or shear loads a thin sheet panel of any given dimensions may be expected to carry, though it is sometimes found that these loads



Longitudinal Stiffener or Stringer (dural)	Transverse Stiffener or Ring (dural)
Thickness = .029in.	Thickness = .0395in.
Developed width = 2.25in.	Developed width = 2.5in.

CYLINDER AND QUADRANT TEST PIECE NO. 1.

FIG. 1.

DETAIL SHOWING METHOD OF CONSTRUCTION.

Skin is connected to stringers and frames by $\frac{3}{32}$in. diameter snap head dural rivets at 1in. pitch with $\frac{5}{16}$in. O/D × 26 S.W.G. dural washers under the rivet heads on the outer surface.

are small and may then be neglected in preliminary strength calculations. It remains, therefore, to choose the best combination of sheet and stiffener for any given loading.

To illustrate a method of approach to this problem we will take a simplified example in connection with the design of a fuselage. For our present purposes we will assume that our fuselage is a tapered circular or elliptical sectioned tube restrained at the front end by inertia or other loads and subject to vertical and horizontal lateral offset loads due to aerodynamic loading of the tail. We will now simplify our example by representing to some extent this fuselage by a circular sectioned cylinder and finding what is its strength: (a) in pure bending, (b) in pure torsion, and (c) in combined bending and torsion. The data obtained from the simplified example may then be utilised in estimating the strength of an actual fuselage. The above simplified example of monocoque construction is relatively cheap to construct and to test, and cylinders of this type have been included in a programme of tests at present being conducted by the Air Ministry.

In the first place a construction was chosen to represent current practice, although it was, of course, realised that this would not give a strength/weight efficiency which could not easily be surpassed. Later, improved constructions were designed and tested. A number of actual fuselages in service were all

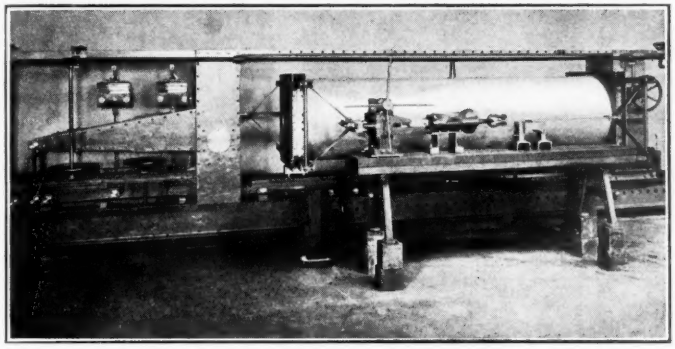


FIG. 2.

found to have weight distribution lying close to the following proportions:—skin 63 per cent., stringers (*i.e.*, longitudinal stiffeners) 20 per cent., and rings (*i.e.*, transverse stiffeners) 17 per cent. This, then, was the weight distribution chosen for the first circular cylinder, which was 12 feet long and 3 feet in diameter. The details of construction are shown in Fig. 1. All component parts were made from duralumin sheet, the skin being of 22 S.W.G. in thickness. The longitudinal stiffeners were of hat section of 22 S.W.G. sheet with the outstanding lips riveted to the inside of the skin by one row each of 1in. pitch rivets 3/32in. in diameter. In this way the skin and each stringer together formed a closed section. The rings were of channel section of 20 S.W.G. sheet with one flange riveted to the inside of the sheet by a single row of 1in. pitch rivets 3/32in. in diameter. The stringers were continuous from end to end of the cylinder and the rings, which were deeper in section than the stringers, were cut away locally and bridged over the stringers.

This cylinder was first tested in pure bending in the following manner. It was mounted horizontally as shown in general view, Fig. 2, and in plan view, Fig. 3. Equal and opposite pure couples in a horizontal diametral plane were applied to each end. Stiff annular plates *AA* (Fig. 3) were bolted to each end of the shell using external angle rings; the end panels of the shell on the compression side

being reinforced by the addition of short extra stringers. Two pairs of parallel beams, *BB* incorporated in the end plates, projected on either side of the shell, and were fitted with loading-shackles *CC*. The shell was mounted in front of a horizontal testing machine and a tensile load was applied by pulling apart the shackles on one side of the shell. A compression load of equal amount was applied by pulling towards each other the shackles at the other side of the shell, using a 5 ton spring balance and straining gear. Dial extensometers were attached in the plane of bending to measure extensions and compressions respectively of two 8-panel lengths, one in the centre on either side of the test specimen.

During the progress of the test, diametral distortions of the central cross-section of the shell were measured vertically, horizontally, and at 45° on either side of the vertical.

Assuming skin and stringers equally effective in load carrying capacity, the failing stress was 5.85 tons/sq. in. This stress was calculated on the simple

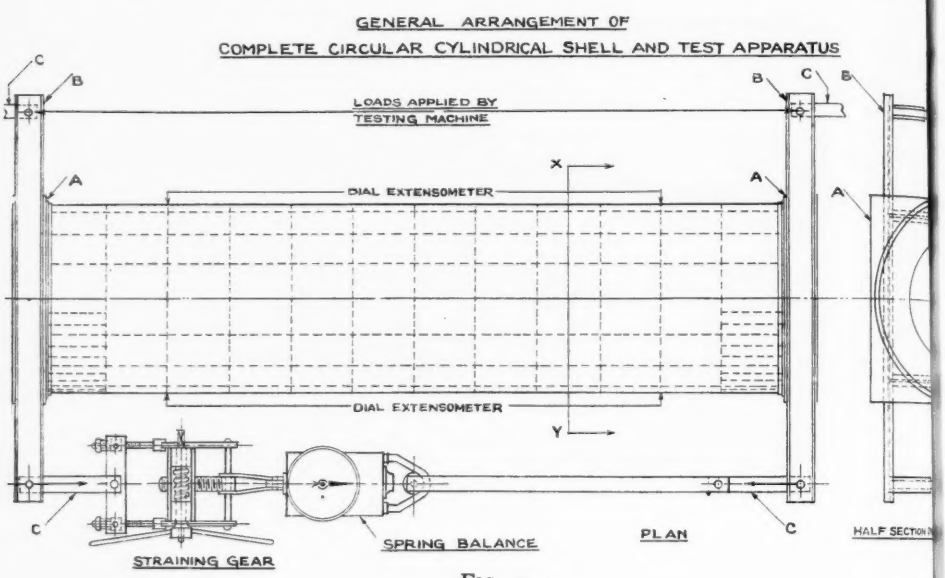


FIG. 3.

assumption that the moment of resistance is equal to the stress multiplied by the modulus of section. Buckling was first observed in the panels on the compression side at a stress of 2.3 tons/sq. in. Up to this stage of the loading (about 40 per cent. of the total load carried) there was no appreciable apparent shift of the neutral axis from the central position, and no appreciable buckling of the panels. The tensile strain on the one side was in close agreement with the compressive strain on the other side, and there was no appreciable deformation of the cross-section of the test specimen at mid-length. At subsequent loads buckling of the panels in compression became evident, the neutral axis shifted gradually to 2.2in. from its original position and the central cross-section progressively developed from a circular to a slightly elliptical shape. Two of the longitudinal stiffeners failed by local buckling on application of the maximum load. When the load was released most of the buckles disappeared, except in the vicinity of the failures of the longitudinal stiffeners. Similar tests have been made on cylinders of two other constructions. The ultimate stresses developed in these cylinders were 7.78 tons/sq. in. and just under 14 tons/sq in. respectively.

In order to investigate the effects of various factors governing the design of this type of structure an alternative cheaper and quicker test was devised which would indicate the strength of the structure in compression with sufficient accuracy for preliminary consideration. The results of these simple tests could, where necessary, be checked by retest of selected constructions in the form of complete cylinders. The first alternative test piece devised took the form of a quadrant of the complete cylinder, 3ft. in length. A general view of this type

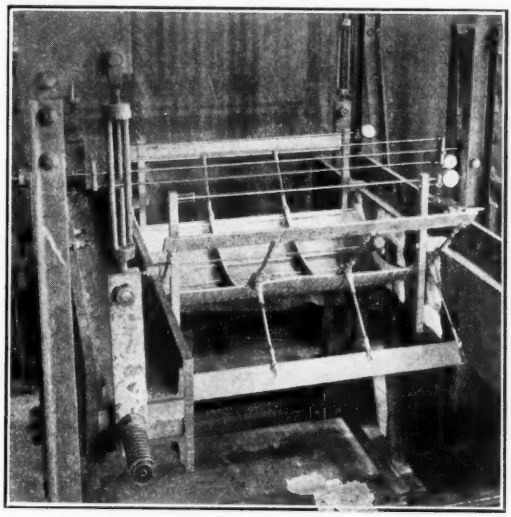


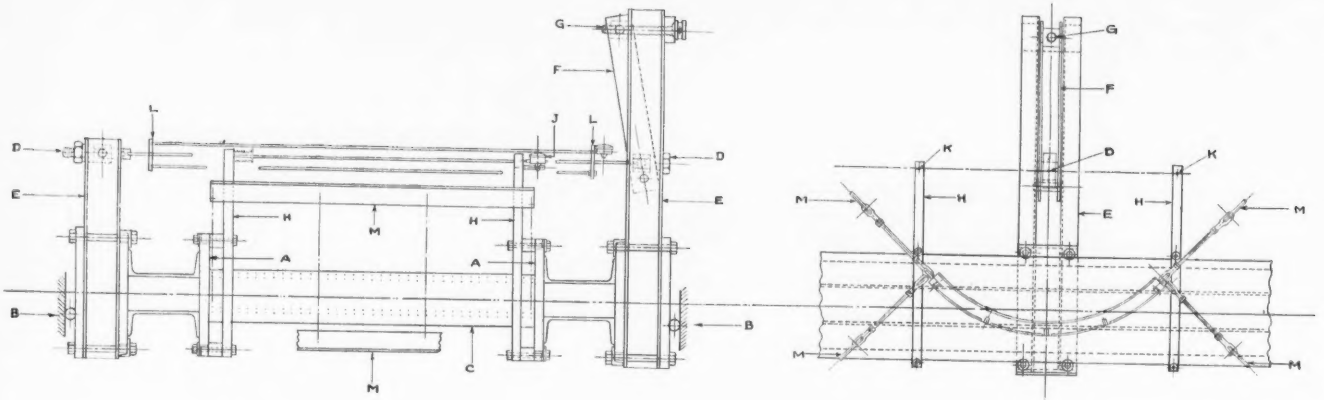
FIG. 4.

of specimen under test is shown in Fig. 4. A general arrangement of the specimen and loading apparatus is shown in Fig. 5.

The quadrant type of specimen was tested in compression with the compressive strain a maximum in the centre of the quadrant and graded in direct proportion to distance from a diametral plane. So far as overall strain parallel to the longitudinal axis of the shell is concerned, the quadrant and the complete shell types of test specimen are similarly strained, provided that the neutral plane in the corresponding complete shell does not move from the longitudinal axis of the shell. During the tests so far made of complete shells, this movement was found to be small, even near collapsing load.

In testing a quadrant specimen, end loads are applied in a horizontal testing machine through rigidly reinforced end plates of box section *AA* (Fig. 5), the line of thrust *BB* being slightly offset, relative to the centroid of cross-section, towards the skin of the test specimen *C*.

Relative rotation of the end plates and the test specimen due to this offset loading is controlled by means of a trimming load in a horizontal tie *DD*, which joins arms *EE* attached to the loading plates *AA*. The longitudinal axis of this tie coincides with the axis of generation of the cylindrical surface of the test specimen. This tie may be virtually shortened by means of a lever *F* and a screw *G*. In this way the loading plates may be rotated back until the lines of intersection between the assumed neutral plane and the respective planes containing the end faces of the test specimen are again at their initial distance apart. This distance is measured directly by means of two pairs of subsidiary arms *HH*



QUADRANT TEST APPARATUS & DIAGRAM OF LOADING

DIAGRAMMATIC REPRESENTATION OF LOADING

FIG. 5.

attached (independently of the loading mechanism) on either side of the test specimen to the end loading plates *AA* and two dial gauges *JJ* connected, one to each pair of arms, by means of light rods *KK* parallel to the direction of loading. The relative magnitudes of the main and trimming loads determine the position of the centre of resistance of the test specimen for any given loading, the trimming load being measured by means of an extensometer *L* mounted on a calibrated portion of the tie rod *DD*.

The ends of the quadrants were cast-in (using a low-melting-point alloy) to a depth of 1in. to prevent local failures due to accidental local concentrations of stress. For quadrant tests so far made, in all but one case the pitch of the rings was the same, *i.e.*, 12in., and the ends of the two intermediate rings were stabilised by being linked up in conjunction with the extremities of the end rings to stiff beams *MM*. There were four such sets of links and beams, two lying in tangential planes, and two in radial planes, relative to the cylindrical surface of the test specimen. A quadrant after test is shown in Fig. 6.

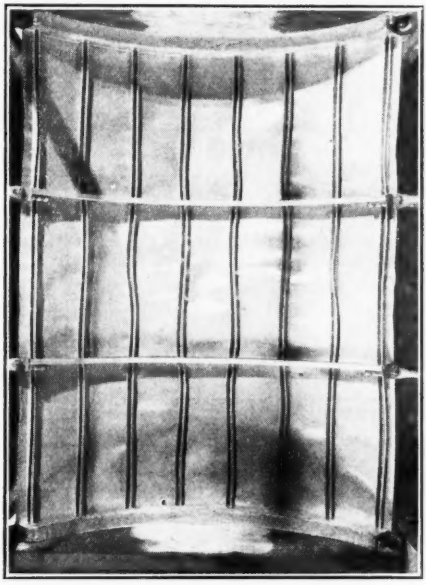


FIG. 6.

The results from sixteen test quadrants are summarised in Table I, together with brief particulars of their constructions which are detailed in Fig. 7. For comparison, the results of the first two complete cylinders are also included in this table.

Economy in testing, rendering possible a corresponding increase in the range of constructions investigated, was carried a stage further by the introduction of compression tests of single panels as shown in Fig. 8. These panels were, in the first case, flat and about 1ft. square, and were reinforced by a single central stringer. A subsequent development was the substitution of a curved panel with two centrally disposed stringers, the width of the resulting sub-panels being equal to the pitch of the stringers as intended in the complete structure. When tested, each specimen was mounted in a vertical testing machine, the curved

FIG. 5. TEST APPARATUS & DIAGRAM OF LOADING

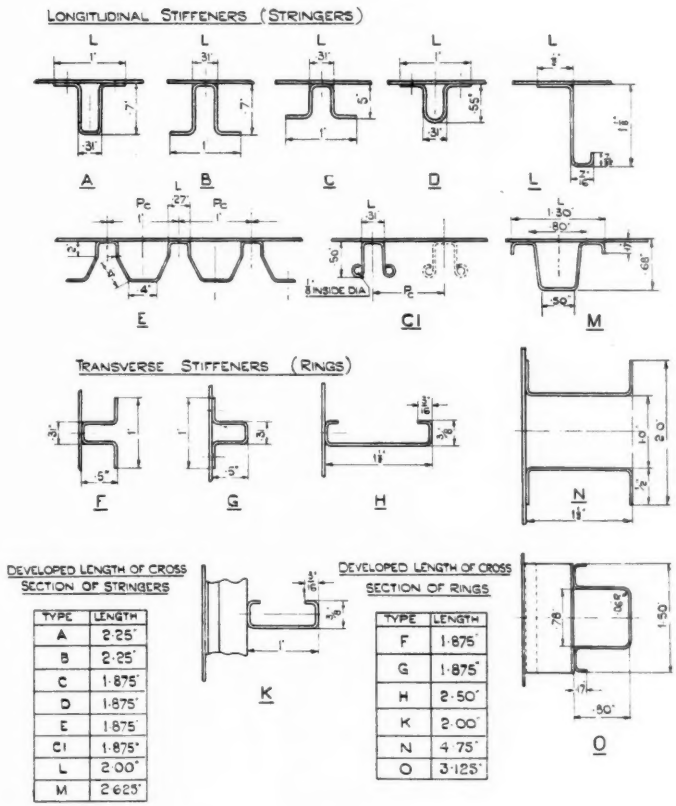
ends being encastered in low-melting-point alloy to a depth of about 1in. Compression was applied parallel to the axis of generation of the cylindrical surface, approximately through the centroid of section, using thick flat steel end plates

TABLE I.

COMPRESSION STRENGTH OF QUADRANTS.

QUADRANT NUMBER		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TOTAL WEIGHT PER SQUARE FOOT OF CONSTRUCTION W LB		0·670	0·670	0·642	0·643	0·507	0·654	0·607	0·623	0·620	0·444	0·603	0·454	0·443	0·473	1·177	0·578
SKIN	THICKNESS t STANDARD WIRE GAUGE	22	22	22	22	28	22	22	22	28	28	28	28	28	24	18	24
	PERCENTAGE OF TOTAL WEIGHT	62·9	62·9	70·5	70·1	53·6	65·4	74·0	70·6	38·1	48·8	39·8	50·2	49·4	61·2	58·6	52·6
STRINGERS	TYPE (SEE FIG. 7)	A	B	C INTERRUPTED BY RINGS	D	D	D	D	D	E	CI	CI	C	C	D	L	M
	THICKNESS t_s STANDARD WIRE GAUGE	22	22	22	22	24	24	24	28	32	24	32	24	24	26	20	24
	Nº PER CIRCLE	16	16	16	16	28	28	16	28	113	28	113	28	28	28	36	20
	CIRCUMFERENTIAL PITCH P_s INCHES	7·07	7·07	7·07	7·07	4·04	4·04	7·07	4·04	1·00	4·04	1·00	4·04	4·04	4·04	3·14	5·76
	PITCH OF RIVETS INCHES	1	1	1	1	½	1	1	1	½	1	1	1	2	1	1¼	1
	PERCENTAGE OF TOTAL WEIGHT	20·0	20·0	18·6	18·8	31·5	23·6	14·5	18·0	52·3	35·9	48·4	34·3	35·1	26·3	28·0	28·1
RINGS	TYPE (SEE FIG. 7)	H	H	F	G	H	H	H	H	K	H	H	H	H	H	N	O
	THICKNESS t_r STANDARD WIRE GAUGE	20	20	22	22	24	24	24	24	24	24	24	24	24	24	20	22
	PITCH P_r INCHES	12	12	12	12	12	12	12	12	12	12	12	12	12	12	18	12
	PERCENTAGE OF TOTAL WEIGHT	17·1	17·1	12·9	11·1	14·9	11·0	11·5	11·4	9·6	15·3	11·8	15·5	15·5	12·5	13·4	19·3
MODULUS OF SECTION	QUADRANT	16·71	16·65	16·00	16·04	11·45	16·22	15·31	15·25	13·69	10·91	14·03	10·79	11·03	12·39	29·54	13·12
	CORRESPONDING COMPLETE CYLINDER	38·40	38·40	37·16	37·08	26·55	37·78	35·54	35·62	33·18	25·26	34·30	25·00	25·55	28·85	70·88	30·92
APPARENT COMPRESSIVE STRESS IN QUADRANT f_q TONS/IN²		5·73	5·45	5·07	5·24	8·39	7·20	5·26	6·06	8·49	5·80	6·94	6·63	6·01	5·77	8·07	8·53
APPARENT COMPRESSIVE STRESS OF COMPLETE CYLINDER f_c TONS/IN²		5·81	–	–	–	7·78	–	–	–	–	–	–	–	–	–	–	–
ESTIMATED FAILING MOMENT OF COMPLETE CYLINDER USING QUADRANT FAILING STRESS IN ALL CASES $M = f_q Z$		219·9	209·3	188·2	194·2	222·8	271·9	186·8	215·9	281·7	146·5	238·1	165·6	153·5	166·5	572·0	256·0
MOMENT OF RESISTANCE / WEIGHT/SQ FT. = $\frac{M}{W}$		328	312	293	302	439	416	308	346	454	330	395	365	346	352	486	443
% STRENGTH / % WEIGHT EFFICIENCY RELATIVE TO 1		100	95	89	92	134	128	94	106	138	101	120	111	106	107	148	135

and a spherical joint for initial alignment of the end faces and their respective loading plates. Diagrams of the test specimen and method of loading are shown in Fig. 9. The results of a large number of these tests are given in Table II. These are for panels with tubular stringers, and their relationship between total weight of structure and load carrying capacity is shown in Fig. 10 and explained in Appendix I.



DEVELOPED LENGTH OF CROSS SECTION OF STRINGERS

TYPE	LENGTH
A	2·25"
B	2·25"
C	1·875"
D	1·875"
E	1·875"
CI	1·875"
L	2·00"
M	2·625"

DEVELOPED LENGTH OF CROSS SECTION OF RINGS

TYPE	LENGTH
F	1·875"
G	1·875"
H	2·50"
K	2·00"
N	4·75"
O	3·125"

FIG. 7.

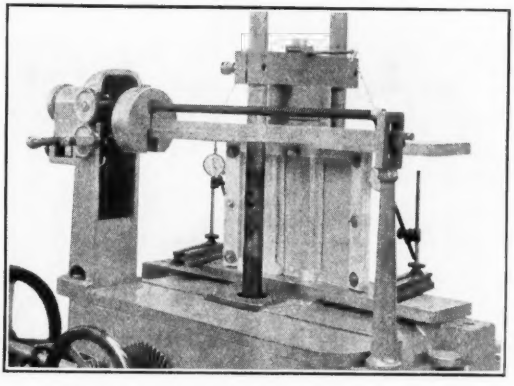
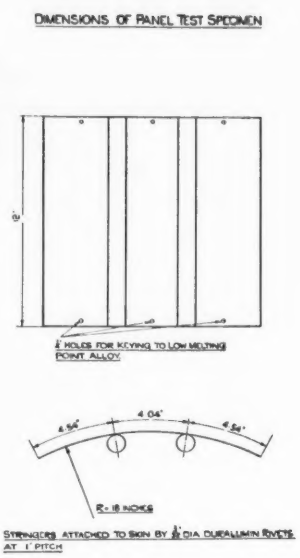
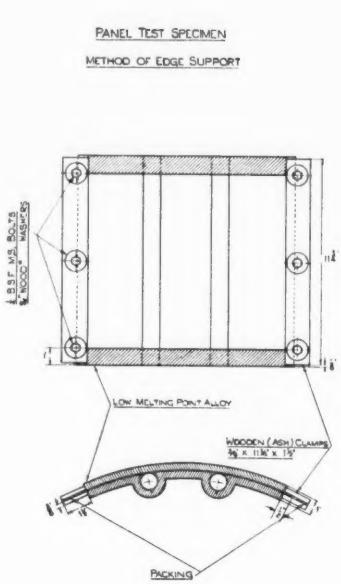


FIG. 8.


DIMENSIONS OF PANEL TEST SPECIMEN
12"
4 HOLES FOR KEYING TO LOW MELTING POINT ALLOY
4.54"
4.04"
4.54"
R= 18 INCHES
STRINGERS ATTACHED TO SKIN BY 1/8" DIA. DURALUMIN RIVETS AT 1" PITCH



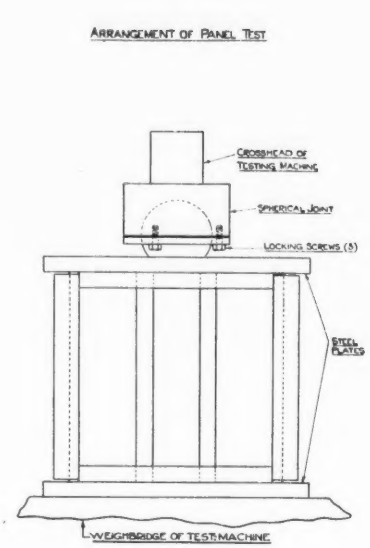


FIG. 9.

TABLE II.

TABLE II.

BENDING STRENGTH OF CYLINDERS.

ESTIMATED FROM RESULTS OF COMPRESSION TESTS OF PANELS WITH TUBULAR STIFFENERS.

PANEL Nº		1	2	3	4	5	5A	6	7	8	9	10	10A	11	12	13	14	15	15A	16	17	17A	18	19	20	20A
TOTAL WEIGHT PER SQUARE FOOT OF CONSTRUCTION W LB.		0·481	0·523	0·582	0·669	0·728	1·259	0·426	0·548	0·629	0·720	0·836	1·365	0·568	0·638	0·722	0·865	1·018	1·555	0·702	0·810	1·337	0·934	1·132	1·382	1·899
SKIN	THICKNESS t STANDARD WIRE GAUGE	28	28	28	28	28	18	28	28	28	28	28	18	28	28	28	28	28	18	28	28	18	28	28	28	18
	PERCENTAGE OF TOTAL WEIGHT	44·9	41·3	37·1	32·3	29·7	59·3	43·6	39·4	34·4	30·0	25·8	54·7	38·0	33·9	29·9	25·0	21·2	48·0	30·8	26·6	55·8	23·1	19·1	15·6	38·3
STRINGERS	OUTSIDE DIAMETER INCHES	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	1	1	1	1	1	1	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$
	WALL THICKNESS STANDARD WIRE GAUGE	24	22	20	18	16	16	24	22	20	18	16	16	24	22	20	18	16	16	24	22	22	20	18	16	16
	PERCENTAGE OF TOTAL WEIGHT	31·5	37·0	43·4	50·7	54·7	31·7	33·5	39·9	47·5	54·2	60·6	37·0	42·0	48·3	54·4	61·9	67·6	44·7	52·9	59·4	35·7	64·7	70·9	76·2	55·7
RINGS (ASSUMED)	PERCENTAGE OF TOTAL WEIGHT	23·6	21·7	19·5	17·0	15·6	9·0	22·9	20·7	18·1	15·8	13·6	8·3	20·0	17·8	15·7	13·1	11·2	7·3	16·2	14·0	8·5	12·2	10·0	8·2	6·0
MODULUS OF SECTION ($Z IN^3$) FOR CORRESPONDING COMPLETE CYLINDER		25·5	28·4	32·4	38·3	42·3	79·6	26·5	30·1	35·5	41·7	49·6	86·5	31·2	35·8	41·4	51·0	61·2	98·7	39·3	47·0	83·3	54·4	67·2	83·5	119·6
AVERAGE COMPRESSIVE STRESS FROM PANEL TEST f_p TONS/IN.^{2}		10·8	11·5	13·1	11·7	12·6	8·4	9·0	13·0	14·3	14·9	14·8	10·2	11·1	14·4	14·4	14·8	16·4	12·2	13·9	12·6	9·3	15·8	16·6	18·5	13·4
ESTIMATED FAILING MOMENT OF COMPLETE CYLINDER ($M = f_p Z$ TONS IN.)		275	327	425	448	533	668	238	391	508	622	734	882	346	516	596	755	1004	1204	546	592	775	859	1115	1545	1604
MOMENT OF RESISTANCE / WEIGHT PER SQUARE FOOT = $\frac{M}{W}$		573	624	730	670	732	531	481	714	807	863	878	646	610	808	826	872	986	774	778	731	579	920	986	1117	845
% $\frac{\text{STRENGTH}}{\text{WEIGHT}}$ EFFICIENCY RELATIVE TO QUADRANT Nº 1 = $\frac{M}{W} \times \frac{100}{386}$		175	190	222	204	223	162	147	218	246	263	268	197	186	246	252	266	301	236	237	223	176	280	301	341	258

MATERIAL:- DUPALUMIN

STRINGERS

CIRCUMFERENTIAL PITCH = 4·04 INCHES

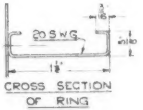
PITCH OF RIVETS = 1·0 INCH

RINGS (ASSUMED)

LONGITUDINAL PITCH = 12·0 INCHES

PITCH OF RIVETS = 1·0 INCH

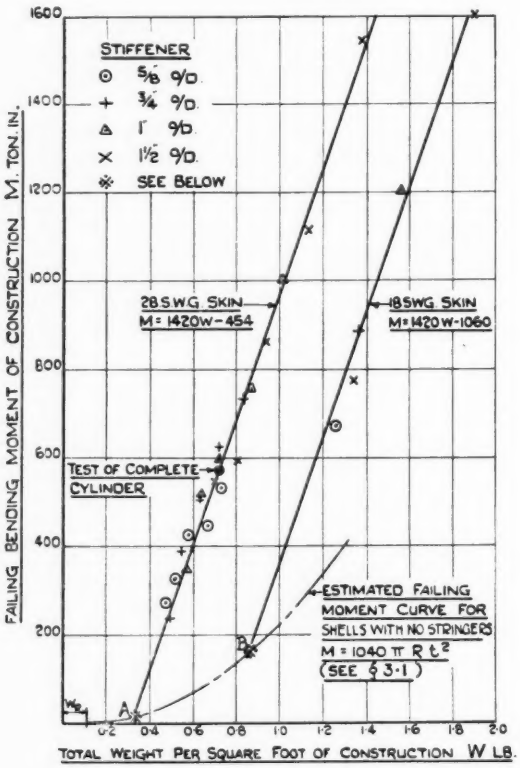
SECTION AS SHOWN →



CROSS SECTION OF RING

NOTE:- ALL CALCULATIONS BASED ON ACTUAL DIMENSIONS OF TUBES AND SHEET.

In general, it has been found that the tests of complete cylinders, quadrants and panels give fairly close agreement in test results for a given construction. This agreement is illustrated in Table III.



	Skin Thickness. 28 S.W.G.	18 S.W.G.
* Estimated failing moments of shells with no stringers (ton-in)	15.3	159.1
Weight/sqr. ft. of skin and rings only (lb.)	0.330	0.860

W_R = weight of rings per sq. ft. of construction = 0.1136 lb.

FIG. 10.

Variation of failing bending moment with weight per square foot for 36in. diameter circular cylindrical shells reinforced with tubular stiffeners at 4.04in. pitch (see Table II).

So far, amongst the many possible variables which affect the behaviour of structures of this type when loaded in compression; (a) the type of loading has been similar in all cases, *i.e.*, it has been either compression due to bending or compression due to direct loading; (b) the curvature of the skin has been the same for all test specimens (*i.e.*, 18in. radius), with few exceptions; (c) the material has been duralumin throughout with one or two exceptions (which have also been light alloys); (d) the relative weights of skins, stringers and rings have been varied through a wide range; (e) the forms of cross-sections of

stringers have been varied, but the form of rings has been the same in the majority of cases; (f) the spacing of stringers has been varied; (g) the spacing of rings has been kept constant (12in.) with only one exception; (h) the rivet pitch has been kept constant with few exceptions.

TABLE III.

COMPARISON OF AVERAGE COMPRESSIVE STRESSES IN COMPLETE SHELL, QUADRANT AND SINGLE PANEL TESTS.

No. OF QUADRANT	CONSTRUCTION				TEST OF CYLINDER	TEST OF QUADRANT	COMPRESSION TEST PORTION OF QUADRANT APPROX 1x1	FLAT PANEL TEST WITH ONE STRINGER APPROX 1x1	CALCULATED FROM STRUT TEST
	SKIN THICKNESS S.W.G.	STRINGERS TYPE	STRINGERS THICKNESS S.W.G.	STRINGERS PITCH INS.					
1	22		22	7·07	5·81	5·73	6·27	5·51	6·29
2	22		22	7·07	–	5·45	5·69	5·62	5·50
4	22		22	7·07	–	5·24	5·61	5·31	–
5	28		24	4·04	7·78	8·39	9·02	8·32	7·89
6	22		24	4·04	–	7·20	6·96	–	7·97
8	22		28	4·04	–	6·06	6·27	–	–
9	28		32	1·0	–	8·49	7·78	–	8·60
10	28		24	4·04	–	5·80	5·72	–	6·47
11	28		24	1·0	–	6·94	6·75	–	7·20
14	24		26	4·04	–	5·77	5·65	–	–

All stresses in tons per square inch.

The various methods of determining experimentally the strength of any given construction have been fairly well established. Amongst the general conclusions reached for direct compression loading or compression loading due to bending, the following may be included:—

A. CONSTRUCTIONS INCORPORATING STRINGERS FORMED FROM STRIP MATERIAL.

(1) "Closed" stringers are more efficient than "Open" stringers, *e.g.*,

Quadrants compared.	Percentage reductions due to the use of open instead of closed section stringers. In maximum developed stress.	In overall efficiency on a strength/weight basis.
1 and 2	5	5
4 and 3	3	3
5 and 12	21	17
9 and 11	18	13

(2) For a given form of construction, reduction in the size of the stringers reduces strength/weight efficiency.

(3) Continuous stringers are advisable, as the use of interrupted stringers involves proper provision for transference of load over the gaps.

(4) The pitch of stringers should be a minimum.

(5) The thickness of skin should be a minimum.

(6) The pitch of rivets joining skin and stringers should be a minimum.

B. Constructions Incorporating Tubular and Open Section Extruded Stringers.

(1) Referring to Fig. 10, the fact that the lines passing through A and B are straight and parallel, leads to the conclusion that increase in strength is directly proportional to increase in stringer weight, and within the range of tests is not appreciably affected by change in the ratios of length of tube/radius of gyration of

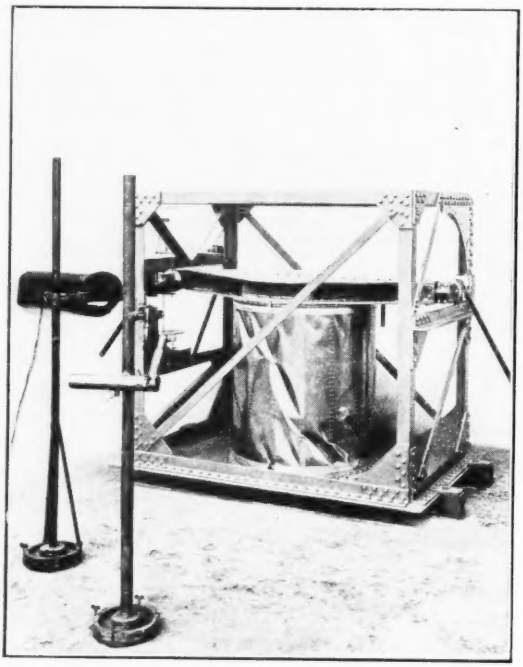


Fig. 11.

tube or wall thickness of tube/radius of curvature of tube, *i.e.*, within a wide range of l/k and t/R ratios of tubular stringers, the strength of structure is increased in proportion to the increase in weight of tubular stringer.

(2) From the results of a few constructions incorporating open extruded section stiffeners, the strength of such structures in direct compression or in bending appears, for a given weight, to be nearly as high as for constructions incorporating tubular stringers (*e.g.*, within 15 per cent.), but the full advantage of stringers of closed over those of open section appears to be more fully realised in cases such as that of a cylinder in combined bending and torsion where waving of the skin occurs consistent with the formation of diagonal tension fields, and troughs and crests of the waves tend to cross the stringers obliquely. This obliquity of the waving of the skin relative to the direction of the stiffeners tends to twist the stiffener and unless the stiffener is relatively stiff

in torsion (as in the case of a tube) premature failure of the structure will occur by early collapse of the stringer. Figs. 12 and 14 show a cylinder with closed stringer at the onset of failure due to torsional loading before and after collapse of the stiffeners. Fig. 6 shows the twisting of open stringers after collapse of a quadrant in compression.

Although efficiency on a strength/weight basis is important it is by no means the only factor to be considered in design. Cost of manufacture, availability of material and facilities for production are amongst other important factors, so that, as in almost all other problems of design, the final result must inevitably be a compromise.

In order to determine the torsional strength and stiffness of selected constructions, four cylinders 3ft. diameter by 3ft. 4in. long were constructed and tested to destruction. A general view of the test is shown in Fig. 11.

Each cylinder was mounted with its axis of curvature vertical as shown, the bottom end of the cylinder being firmly attached to the base of a test frame and the top to a stiff transverse built-up loading plate. Torsion was applied by means of two horizontal hydraulic rams which applied a couple to the loading plate in a horizontal plane, reactions of the rams being transmitted to the frame through pairs of hardened and ground vertical ball-bearing plates. A summary of the results of these tests is given in Table IV. A cylinder just prior to failure is shown in Fig. 12, and cylinders after failure are shown in Figs. 13 to 15.

TABLE IV.

SUMMARISED RESULTS OF PURE TORSION TESTS.

Cylinder No.	1	2	3
Construction similar to quadrant No.	1	5	9
Failing torque, ton-in.	249	132	197
Failing torque stress, ton/in.^{2}	3.22*	2.54*	2.97*
Weight, lb. per sq. foot	0.67	0.507	0.62
Nominal skin thickness, in.	0.028	0.0148	0.0148
Percentage weight of skin	62.9	53.6	38.1
Weight of skin, lb. per sq. ft.	0.42	0.27	0.236
Percentage weight of stiffeners	20.0	31.5	52.3
Percentage weight of rings	17.1	14.9	9.6
Pitch of stiffeners or corrugations, in.	7.07	4.04	1.00
Failing torque/weight	100	70	85
Torsional stiffness/weight	100	58	83
Failing torque/weight of skin	100	83	141
Torsional stiffness/weight of skin	100	68	137
Shear stress in skin, f ton/in.	4.37†	4.39†	6.55†
Diagonal tension in skin, f_D ton/in.^{2}	8.74	8.78	13.1
Compressive stress in stringers, f_s ton/in.^{2}	7.56	4.13	2.86
Compressive stress in rings, f_r ton/in.^{2}	12.67	12.50	23.6

* Including stringers. † Not including stringers.

Two of the above constructions have also been tested in combined bending and torsion. In this case the cylinders were also 3ft. diameter, but were 9ft. 11in. in length. A general view of one of these last cylinders under test is shown in Fig. 16. The method of mounting the specimen was similar to that used for pure torsion tests, except that in this case the test frame was extended to accommodate the extra length of specimen and the hydraulic rams instead of being horizontal were inclined at an angle of 45° to the horizontal for the tests to destruction, the results of which are given in Tables V and VI. The relationships between pure bending, pure torsion, and combined bending and torsion failing moments are shown in Fig. 17. Cylinders after failure are shown in Figs. 18, 19 and 20.

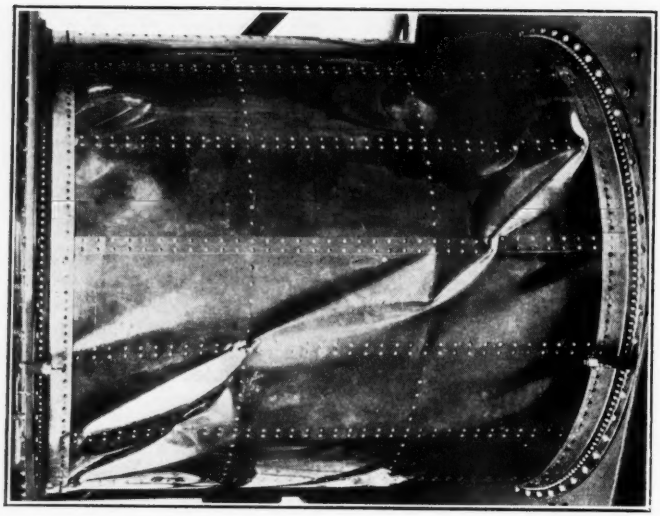


FIG. 13.

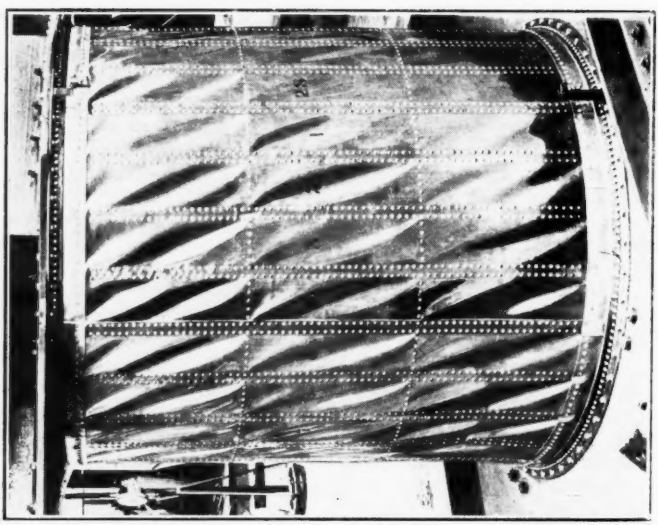


FIG. 12.

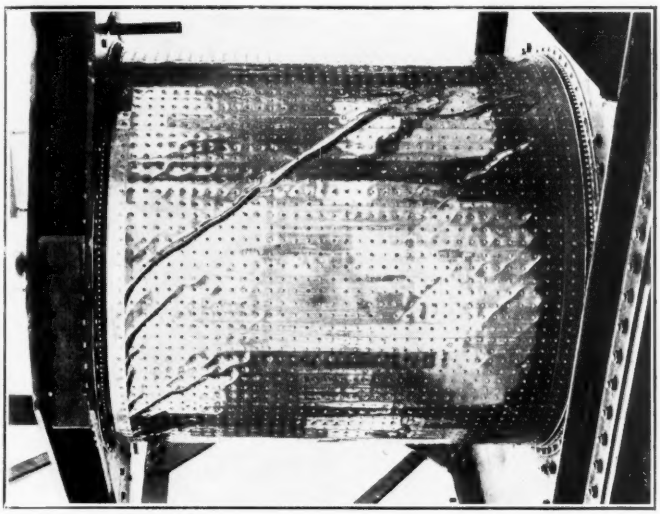


FIG. 15.

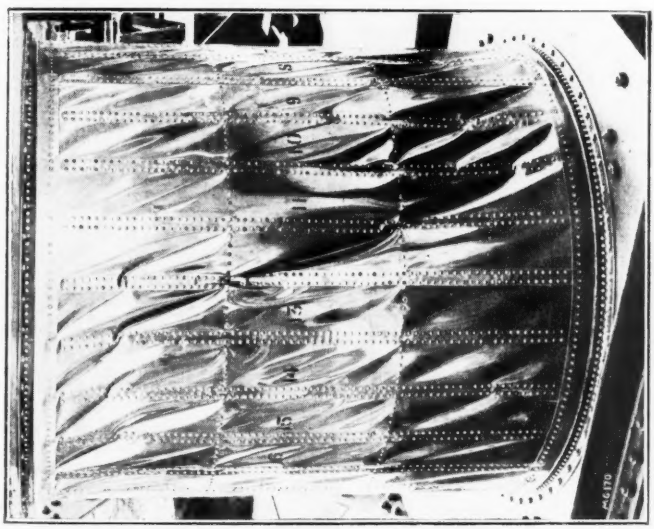


FIG. 14.

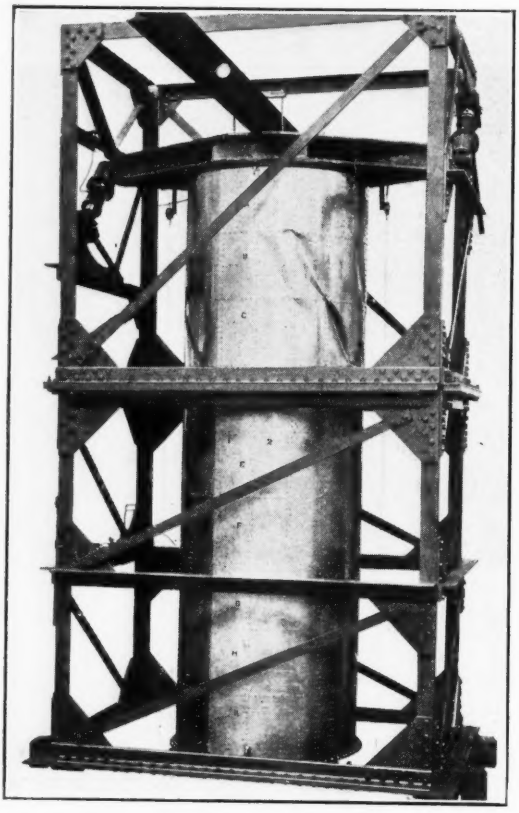


FIG. 16.

TABLE V.

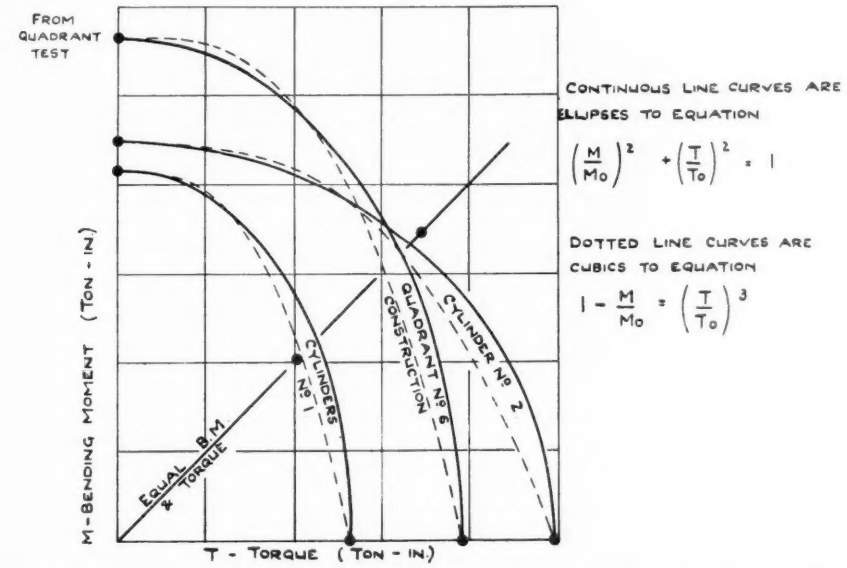
SUMMARISED RESULTS OF COMBINED BENDING AND TORSION TESTS.

Cylinder No.	1	2
Construction similar to quadrant No.	1	5
Failing moment, ton/in.	245	144
Torque component = bending moment, ton/in.	173	102
Stresses due to torque—		
Shear stress in skin, f ton/in.^{2}	3.04	3.39
Diagonal tension in skin, f_d ton/in.^{2}	6.08	6.78
Compressive stress in stringers, f_s ton/in.^{2}	5.78	3.42
Compressive stress in rings, f_r ton/in.^{2}	8.43	9.48
Stresses due to bending—		
Tensile stress in skin, f_t ton/in.^{2}	5.70	4.50
Compressive stress in stringers, f_s ton/in.^{2}	10.04	6.32
Maximum stresses due to combined bending and torsion—		
Principal tensile stress in skin, f_p ton/in.^{2}	7.02	6.32
Maximum total compressive stress in stringers, f_{ts} ton/in.^{2}	15.82	9.74

TABLE VI.

FAILING MOMENTS OF CYLINDERS TESTED IN VARIOUS WAYS.

Type of loading.	Symbol.	Derivation of figure. (See figure 17).	Failing Moment (ton-in.) Cylinder No. 1.	Cylinder No. 2.	Cylinder of same construction as Quadrant No. 9.
Pure bending	M_o	Tests	223	207 282	{ Estimated from test of quadrant }
Combined bending and torsion	Bending component M	Tests	173	102	—
		Ellipse	166	111	161
		Cubic	161	104	157
	Torsion component T	Tests	173	102	—
		Ellipse	166	111	161
		Cubic	161	104	157
	Resultant moment	Tests	245	144	—
Pure torsion	T_o	Tests	249	132	197
Total weight per square foot of construction lb.			0.67	0.507	0.62


FROM QUADRANT TEST
CONTINUOUS LINE CURVES ARE ELLIPSES TO EQUATION
$\left(\frac{M}{M_o}\right)^2 + \left(\frac{T}{T_o}\right)^2 = 1$
DOTTED LINE CURVES ARE CUBICS TO EQUATION
$1 - \frac{M}{M_o} = \left(\frac{T}{T_o}\right)^3$
M - BENDING MOMENT (TON - IN)
T - TORQUE (TON - IN.)
EQUAL B.M & TORQUE
CYLINDERS Nº 1
QUADRANT Nº 9 CONSTRUCTION
CYLINDER Nº 2

RELATIONSHIP BETWEEN BENDING & TORSION FAILING MOMENTS OF CYLINDERS.

FIG. 17.

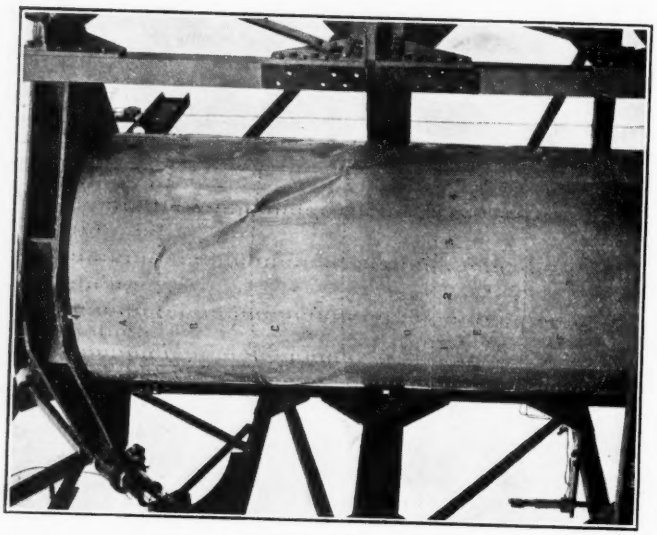


FIG. 19.

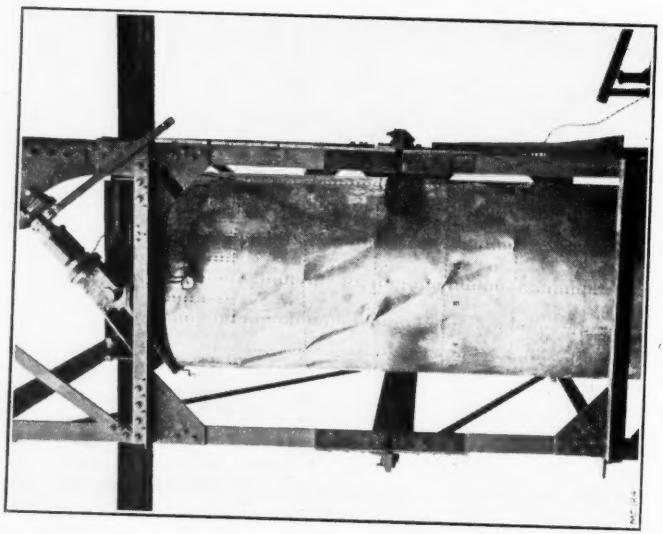


FIG. 18.

Before testing the 3ft. and the 9ft. long cylinders to destruction, two series of preliminary torsional stiffness tests were made on each. Each test in one series included a constant applied torque, and each test in the other series was made with a constant ratio of torsional and flexural applied moments.

In the first series the hydraulic rams were horizontal and torque-twist diagrams were obtained with given bending moments maintained constant throughout each test and applied by means of a transverse lever bolted on top of and at right angles to the torque arm as shown in Figs. 16 and 18. A dead weight was applied to one end of this beam and an equal upload was applied to the other end of the beam.

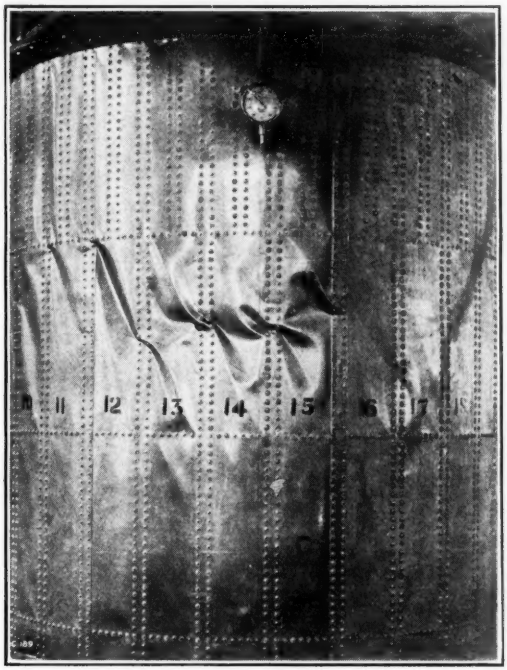


FIG. 20.

In the second series of tests the ratio of flexural moment to torque was varied by inclining the rams at every 15° from horizontal to vertical, the horizontal giving pure torque and the vertical giving flexure without torque.

The results of the torsional stiffness tests on the shorter cylinders were more erratic than those obtained from the tests of the longer cylinders, but the final conclusion reached is that, within the elastic limit of the structure, the torsional stiffnesses of the constructions tested are not appreciably affected by the presence of flexural moments.

Estimated stresses due to pure bending, pure torsion and combined bending and torsion are shown in Table VII and Fig. 21. The method of calculating these stresses is given in Appendix II.

TABLE VII.

STRESSES IN COMPLETE CYLINDERS UNDER VARIOUS FORMS OF LOADING.

Construction.	Cylinder No. 1.	Cylinder No. 2.
Tension in skin—		
Bend test	7.29	9.18
Torsion test	8.74	8.78
Combined bending and torsion test ..	7.02	6.32
Compression in stringers—		
Bend test	12.64	13.01
Torsion test	3.78	2.06
Combined bending and torsion test ...	12.93	8.03
Compression in rings—		
Torsion test	6.33	6.25
Combined bending and torsion test ...	4.21	4.74

All stresses in tons/sq. in.

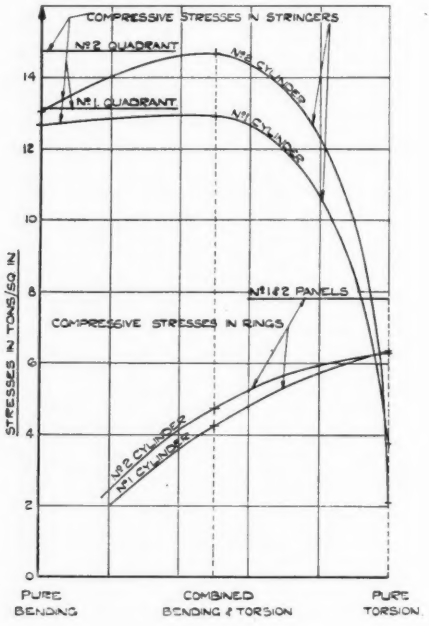


FIG. 21.

Stresses in complete cylinders under various forms of loading.

In order to investigate the effect on strength of insertion of reinforced holes representing cockpit openings in monocoque fuselages, the first two 12ft. long cylinders were repaired and re-tested in pure bending, each with a reinforced hole approximately 10in. in diameter in the middle of the compression side. Subsequently each cylinder was again repaired and fitted with an 18in. diameter reinforced hole. Details of the construction of these holes are given in Fig. 22, and the results are summarised in Table VIII.

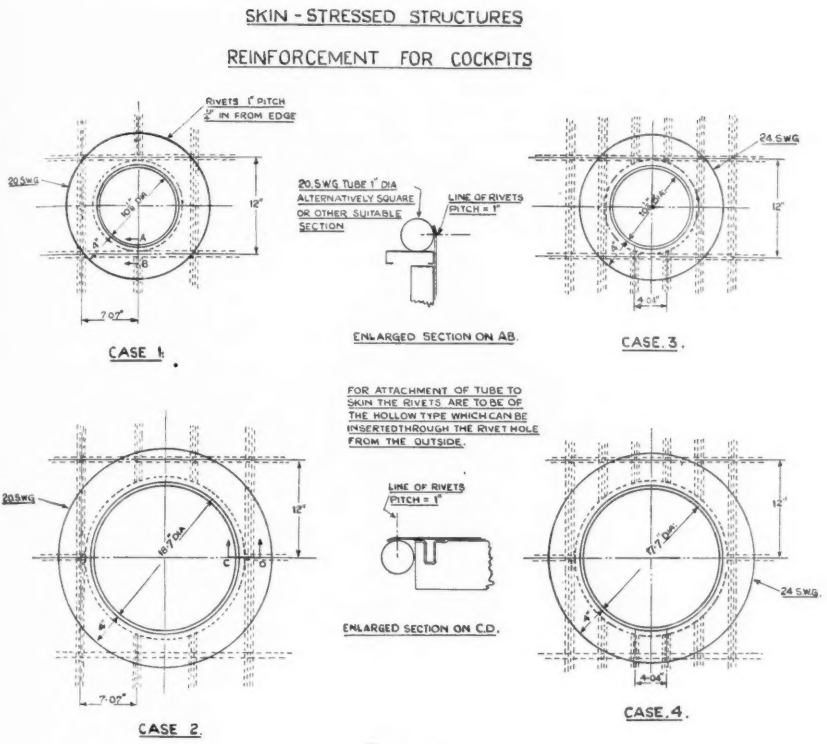


FIG. 22.

TABLE VIII.

RESULTS OF TESTS OF CYLINDER WITH REINFORCED HOLES.

	Cylinder No. 1. Construction similar to Quadrant No. 1.		Cylinder No. 2. Construction similar to Quadrant No. 5.	
	Failing bending moment Ton-in.	Net added weight. lb.	Failing bending moment. Ton-in.	Net added weight. lb.
No hole ...	223 (100)	—	202 (100)	—
Small hole ...	225 (101)	0.69	194 (96)	0.53
Large hole ...	197 (88)	0.43	171 (85)	0.37

This kind of practical design information should now be extended by further tests on cylinders with larger holes and on cylinders with concentrated loads applied to end lugs similar to those used for attachment of fuselage and wings.

A decision as to which is the best method of picking up a concentrated load is not easy to attain, but it would probably be attained with greater confidence if founded on mechanical tests of an actual structure rather than on calculations based on assumptions which are, at the present stage of theoretical analysis, of doubtful accuracy.

Meanwhile, the possibility of using small test portions of a complete structure instead of the whole structure will considerably reduce the cost and should increase the speed of development of the design of hulls, monocoque fuselages, and metal covered wings in general.

In conclusion, I should like to acknowledge the assistance given by Dr. B. G. Dickins, formerly of the Royal Aircraft Establishment, in making a large number of panel tests and by Mr. H. J. Pollard and Mr. S. G. Nash, of the Bristol Aeroplane Company, in making tests of complete cylinders.

I am indebted to the Air Ministry for permission to read this lecture, and accept all responsibility for opinions expressed or implied.

Appendix I.

Method of Drawing the Diagram in Fig. 10.

The ordinate of each plotted point represents the failing bending moment (estimated from the test of a panel) of a complete 36in. diameter cylindrical shell reinforced with a particular tubular stiffener at 4.04in. circumferential pitch. The abscissa of each plotted point represents the weight per square foot of the complete construction, allowing for the rings shown at the foot of Table II spaced at 12 inches pitch. In drawing the diagram the weight per square foot due to the assumed rings is first marked off on the horizontal axis; the curve AB is then drawn to represent the estimated failing moments of shells with no stringers. From panel tests of curved sheets with no stringers it was established that the buckling stress for duralumin sheet was $1{,}040\ t/R$ tons per square inch. The modulus of section is, of course, $\pi R^2 t$ so that the equation of the curve AB is

$$M = 1{,}040\ \pi R t^2.$$

Point A represents an imaginary cylinder with 28 S.W.G. skin and no stringers, *i.e.*, with skin and rings only. The corresponding points for all the cylinders with 28 S.W.G. skin and tubular stringers calculated from the corresponding panel tests and the actual experimental result from the test of a complete cylinder all lie close to a line passing through this point A. The equation of this line is

$$M = 1{,}420\ W - 1{,}060.$$

Generally, the equation for 36in. diameter circular sectioned cylinders of skin thickness t incorporating solid drawn tubular stringers is

$$M = 1{,}420\ W + c.$$

Assuming similar relationship for other thicknesses of sheet, the constant c may be shown to be

$$58{,}700\ t^2 - 1{,}420\ (Wr + 14.4\ t)$$

where Wr is the weight in pounds of the rings per square foot of construction ($Wr = 0.1136$lb. for rings assumed in this series of cylinders).

Appendix II.

Method of Calculating Stresses in Cylinders under Various Forms of Loading.

Fig. 21 shows the failing loads of the two types of structures under pure bending, combined bending and torsion and pure torsion, together with control tests of quadrants and single panels of similar constructions.

The compressive stresses in the stringers for pure bending were calculated on the assumption that only a portion of the skin immediately adjacent to the stringers is capable of carrying compressive stresses. In calculating the modulus of section on this basis, therefore, the middle portion of each panel on the com-

pressive side is neglected and only the stringers and the adjacent strips are taken into account. The assumed effective width of skin on either side of the stringer is defined in Appendix III. In calculating compressive stresses in the stringers for pure torsion, etc., it was assumed that part of the shear due to torsion was taken directly by the skin and part by tension diagonal field. The method of estimating approximately stresses due to tension diagonal fields is given in Appendix IV.

In general, for cases involving torsion, it appears convenient to divide constructions into three classes according to the ratio of skin thickness to minimum superficial dimension of panel, *i.e.*:—

(1) Where this ratio is, say, 1/500 or less;

(2) Where this ratio is, say, 1/50 or more; and

(3) Where this ratio lies between 1/500 and 1/50.

For class (1) constructions, the diagonal tension field method is used as outlined in Appendix IV; for class (2) constructions, the shear is assumed to be taken directly in the skin; for class (3) constructions, part of the shear may be assumed to be taken by diagonal tension fields and part directly in the skin.

As the ratio of skin thickness to minimum superficial dimension of both the constructions at present under consideration was approximately 1/275, it was assumed that half the shear was taken by diagonal tension field and half by direct shear.

In calculating the compressive stresses in stringers for the cases of combined bending and torsion, as the stringers of No. 1 cylinder failed at the junction with the rings, the maximum stress developed was assumed to be the sum of that due to bending and that due to compression arising from diagonal tension field.

For No. 2 cylinder, failure occurred in the middle of the stringer and in addition, therefore, to the above two compressions a further allowance (6.63 tons per square inch) was made for compression due to bending of the stringer itself, arising from the hoop tension component of the diagonal tension fields.

It will be noticed that the compressive stresses of the stringers are in close agreement with the compressive stresses developed in the quadrants for both the pure bending and combined bending and torsion cases of loading.

For the pure torsion case of loading, the compressive stress developed in the rings is clearly the criterion of failure. These stresses are in fair agreement with the compressive stresses developed in panels incorporating sections of rings.

Appendix III.

Approximate Estimation of Stresses in a Stiffened Circular Sectioned Cylinder in Bending.

On the tension side, all skin and stringers are assumed to be equally effective in carrying tension.

On the compression side, the stringers and a limited width of skin only are considered effective in carrying compression. This width of skin extends a distance "w" on either side of the row(s) of rivets joining the skin and stringer and, where there are two such rows of rivets, includes also the width of skin between the rows.

$$2w = 1.7\, t\sqrt{(E/f_s)}, \quad (1), \quad (2), \quad (3),$$

where E is Young's modulus for the material,

f_s is the compressive stress in the stringer (and adjacent skin as defined above) at failure, and

t is the thickness of the skin.

Appendix IV.

Approximate Estimation of Stresses in a Stiffened Circular Sectioned Cylinder under Torsion, where the Ratio of Skin Thickness to Minimum Dimension of Panel is 1/500 or less (4).

Notation.

Let f = average shear stress in skin, neglecting stringers.
f_d = diagonal tension stress in the skin. (For simplicity this is assumed to be at an angle of 45° to the longitudinal axis of cylinder. Actually the angle will probably be between 40° and 42°.)
f_h = hoop tension stress in the skin.
f_a = axial tension stress in the skin.
f_s = compressive stress in stringers and adjacent skin.
f_r = compressive stress in rings and adjacent skin.
t = thickness of skin.
R = radius of curvature of skin.
n = number of stringers.
P_s = pitch of stringers = $2\pi R/n$.
P_r = pitch of rings.
A_s = effective cross-sectional area of each stringer and adjacent skin. (This is estimated on the same basis as is used for the compression side of the cylinder in Appendix III.)
A_r = effective cross-sectional area of each ring and adjacent skin. (Estimated on the same basis as A_s.)
T = applied torque.
w_s = centripetal load per inch run of stringers.
f_{BMS} = bending moment stress in stringers.
Z_s = section modulus for bending (about axis parallel to tangent of cylinder) for stringer and adjacent skin.

Assuming all shear and tensile loads to be taken by the skin and all compressive loads to be taken by the stiffeners (stringers and rings + adjacent skin)

$$f = T/2\pi R^2 t$$
$$f_d = T/\pi R^2 t$$
$$f_h = T/2\pi R^2 t$$
$$f_a = T/2\pi R^2 t$$
$$f_s = (T/2\pi R^2)(P_s/A_s) = f \cdot t\,(P_s/A_s) = T/RnA_s$$
$$f_r = (T/2\pi R^2)(P_r/A_r) = f \cdot t\,(P_r/A_r)$$
$$w_s = (T/2\pi R^3)\,P_s = T/nR^2$$
$$f_{BMS} = (T/nR^2)(P_r^2/12\,Z_s) \text{ at ends and } (T/nR^2)(P_r^2/24\,Z_s) \text{ at centre.}$$

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ABSTRACTS AND NOTICES

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Behaviour of Turbulent Boundary Layers on Curved Convex Walls. (H. Schmidbauer, N.A.C.A. Tech. Memo. No. 791, April, 1936.) (43/1 1987 U.S.A.)

In an approximate method for calculating the friction layer at a plane plate when the former is simultaneously subjected to a pressure gradient parallel to the plate, E. Gruschwitz (Ing.-Arch., II, 1931) developed a system of linear differential equations for a suitably chosen form parameter which indicated the approach of separation and the so-called "boundary layer thickness."

This system of equations is extended here to the case where the friction layer is subject to centrifugal forces. Measurements were made of the total pressure in the friction layer during flow of an air current along the upper curved surface of an upwardly curved channel between two parallel, perpendicular walls, the curvature of which was constant. Experiments were made for three different radii of curvature, $r = 25$, 75 and 150 cms. Evaluation of the data showed that change in momentum and wall drag are functions of the ratio boundary layer thickness/radius of curvature of the wall. Transition from laminar to turbulent flow occurs at somewhat higher Reynolds numbers at the convex wall than at the flat plate, due to the stabilising effect of the centrifugal forces.

The extended system of equations is applied to several boundary layers. For comparison, two examples for friction layers without curvature were also calculated. It was found in each case that for a level plate the friction layer was about 25 per cent. thicker than that for a wall with convex curvature.

New American Wind Tunnel. (Engineer, Vol. 163, No. 4239, 9/4/37, p. 419.) (43/2 5506 U.S.A.)

The United States Government has placed a contract valued at about 1,000,000 dollars for the construction of a high-pressure wind tunnel for aeronautical experimental work. The tunnel will be 280ft. long with a diameter varying from 19ft. to 54ft. at its widest point. A wind velocity of 200 miles an hour will be created within the tunnel by a 30ft. diameter multi-blade propeller, driven by an 8,000 b.h.p. electric motor. About 2,000 tons of steel will be used for the tunnel, which will be built up by welding steel plates of varying thicknesses between $\frac{3}{8}$in. and 2in.

The Interference Effect of the Surface of the Sea on the Lift of a Seaplane. (S. Tomotika and I. Imai, Aer. Res. Inst. Tokio Rept., Vol. 12, No. 143, Feb., 1937, pp. 71-128.) (43/3 5532 Japan.)

The appreciable interference effect on the lift of a seaplane produced by flying near the surface of the sea, and which according to experiments carried out at Felixstowe may produce a 10 per cent. increase in the maximum lift cannot be satisfactorily explained by the ordinary vortex theory. In this paper a mathematical analysis is made of the problem of calculating the lift of a flat plate placed in a two-dimensional continuous stream of fluid which is bounded by a free surface on the lower side of the plate, assuming various values for the angle of attack of the plate and for the distance of the plate from the free surface. It is shown that for practically important angles of attack, such as 10° or 15°, the lift is increased by a few per cent. due to the presence of the free surface when the distance of the plate from it is of the same order of magnitude as the breadth of the plate. The surface of the sea being considered as a free surface, by assuming the water at rest and neglecting gravity, the theoretical results are applied to the case of a seaplane taxying over the sea surface, and it is shown that for an angle of attack of about 15° the maximum lift may be expected to be increased by about 6 per cent. when the distance of the wing from the surface is of the order of the breadth of the wing.

Sphere Tests in the N.A.C.A. 8-foot High-Speed Tunnel. (R. G. Robinson, J. Aeron. Sci., Vol. 4, No. 5, March, 1937, pp. 199-201.) (43/4 5632 U.S.A.)

Tests with a 4in. sphere indicate that this high speed channel possesses practically free air turbulence. Tests with a 12in. sphere in the entrance cone (low speed) showed a critical Reynolds number of the order of 200,000, so that the 9/1 entrance cone fitted to this channel has reduced the turbulence from 1 per cent. at entry to less that 0.3 per cent. in the working section. Compressibility effects affect turbulence measurement of this type at speed in excess of 270 m.p.h.

Measurements of Intensity and Scale of Wind Tunnel Turbulence and their Relation to the Critical Reynolds Number of Spheres. (H. L. Dryden, G. B. Schubauer, W. C. Mock, and H. K. Skramstad, N.A.C.A. Report No. 581, 1937.) (43/5 5823 U.S.A.)

By the use of a modification of the usual hot wire apparatus incorporating two hot wires suitably connected and mounted so that the cross-stream distance between them may be varied, it has been found possible to determine the correlation between the speed fluctuations existing at the two wires. If u_1 and u_2 are the velocity fluctuations in the direction of the mean speed at the first and second wires respectively, a correlation coefficient $R(y)$, equal to $\overline{(u_1 u_2)} / \{ \sqrt{(\overline{u^2})} \sqrt{(\overline{u_2^2})} \}$ may be found as a function of the separation y. A length characterising the scale of the turbulence may then be defined by the relation—

$$L = \int_0^\infty R(y)\, dy.$$

It was found that the critical Reynolds number depended on D/L, where D is the diameter of the sphere, as well as on $\{ \sqrt{(u^2)} \} / U$. It is shown that the effect of the size of the sphere already observed by other investigators is but a particular manifestation of the foregoing more general relation.

Notes on the Construction of Integral Fuel Tanks for Aeroplanes. (H. J. Alter, J. Aer. Sci., Vol. 4, No. 3, Jan., 1937, pp. 100/106.) (43/6 5238 U.S.A.)

The integral or built-in tank saves weight and space in aeroplane structures and thus makes for efficiency. Low rivet stresses, careful workmanship and

above all an efficient sealing medium such as bakelite varnish or a synthetic rubber compound (Thiokol or Duprene) are required. Several ways of making the seams and joints are illustrated, the best type of seam being one which is securely fastened at the ends and has a flexing portion between. Corners and structural members going through the tank present the most difficulty. These should be fastened on with properly shaped castings, stamped or welded fittings. Standard dural tanks weigh approximately 0.47 to 0.38lb. per gallon, depending on size (150 gallons to 500 gallons). The integral tank weights for various installations come out as follows:—

100	gallons	...	...	0.32 lb./gallon.
300	,,	...	...	0.18 ,,
500	,,	...	...	0.10 ,,
1,000	,,	...	...	0.06 ,,

The possible saving in weight is thus considerable.

Variable Pitch Propeller. (British Patent No. 460,921.) (G. Schwarz, Engineer, Vol. 163, No. 4239, 9/4/37, p. 430.) (43/7 5508 Great Britain.)

This variable pitch propeller is automatically adjusted according to the temperature, not the pressure, of the atmosphere in which it is working. Fixed to the blade of the propeller there is an arm loaded with an eccentric weight, which tends to turn the blade anti-clockwise on account of centrifugal force. Between the arm and an abutment on the propeller boss there is a telescopic link. The casing of this link is filled with a liquid, such as oil, which, expanding and contracting under the influence of changes of temperature, acts on the plunger and adjusts the pitch of the propeller in opposition to the action of the weight. The temperature of the casing may be under the control of the pilot through the diversion of part of the engine exhaust.

Stinson Reliant Wing Structure. (Aero Digest, Vol. 30, No. 4, April, 1937, p. 72.) (43/8 5607 U.S.A.)

Due to the airfoil section and plan form of the wing, which is a Clark Y section, tapered and modified, each wing rib must be constructed in a separate jig. These ribs are built of square dural tubing, riveted together. The Y, or inboard, section of the spar (fuel tank in middle of Y) is also built in a separate jig, as is the outer portion of the spar. These are constructed of chrome molybdenum steel. The false spar to the rear, together with the aileron and flap, are built of dural and are individually jigged so as to be interchangeable on any wing. Both sections of the spar, together with ribs, torque vees and false spar, are assembled in another jig. The dural leading edge, false wing tip, heavy gauge aluminium tank, cables and wiring, are installed after the wing has been removed from the assembly jig.

Full-Scale Wind Tunnel and Flight Tests of a Fairchild 22 Aeroplane Equipped with a Zap Flap and Zap Ailerons. (C. H. Dearborn and H. A. Soulé, N.A.C.A. Tech. Note No. 596, March, 1937.) (43/9 5625 U.S.A.)

A wing equipped with Zap flaps and Zap ailerons was tested on a Fairchild 22 aeroplane in the full-scale wind tunnel and in flight. The Zap flap is a split flap characterised by the fact that its leading edge is moved aft as the flap angle increases, so that the trailing edge of the flap remains approximately under the trailing edge of the wing. The Zap ailerons are small chord aerofoils fitted with leading edge slats, the aileron being mounted above and slightly forward of the trailing edge of the wing. Both tunnel and flight experiments showed that the flaps and ailerons functioned satisfactorily. The Zap ailerons require, however, relatively large stick forces for their operation.

High Altitude Aeroplane Compartments. (J. S. McDonnell, J. Aeron. Sci., Vol. 4, No. 5, March, 1937, pp. 177-182.) (43/10 5026 U.S.A.)

Experiments were carried out in the Bureau of Standards decompression chamber on the effect of rapid evacuation on the human organism (puncture of aeroplane compartment at high altitude). Structural tests were also carried out on various types of compartments (fixed and floating skin) with the object of getting information on weight of skin to withstand the pressure difference. The author concludes that sealed pressure compartments can be successfully constructed for altitudes up to 30,000 feet and that the sudden decrease in pressure due to a puncture will not prove dangerous to the passengers.

Strength of Welded Aircraft Joints. (W. C. Brueggeman, N.A.C.A. Report No. 584, 1937.) (43/11 5822 U.S.A.)

In welding thin-walled tubing, the recently developed "carburising flux" process was found to be the only method capable of producing joints free from cracks. The "magnetic powder" inspection was used to detect cracks in the joints and flaws in the tubing. The strengths of chromium-molybdenum T, lattice, and butt joints were materially increased by heat treatment. Butt joints in chromium-molybdenum sheet and tubing welded with low carbon and chromium-molybdenum welding rod and those welded by the "carburising flux" process had about the same strength in the "as welded" condition. The chromium-molybdenum and carburising flux welds were the strongest after heat treatment.

U.S.A. New Method for Wing Load Calculation. (Inter Avia., No. 422, 13/4/37, p. 6.) (43/12 5847 U.S.A.)

The Army-Navy-Commerce Committee on Aircraft Requirements recently published their first bulletin (A.-N.-C. Structures Bulletin No. 1), in which a method for obtaining a spanwise load distribution on wings is described. The spanwise distribution of *CL* (lift coefficient) and *CD* (drag coefficient) are obtained by the solution of a Fourier series with a correction at the tip for the value of *CL*. Charts are set up for the analytical solution of the problem, with an example worked out. Curves are included for the ready solution of the Fourier series for untwisted tapered monoplane wings, having a straight trailing and leading edge. The report was prepared by the Navy Department, Bureau of Aeronautics, and has been approved by the military and commercial departments.

Down Gusts. (J. H. Crowe, Airc. Eng., Vol. 9, No. 99, May, 1937, pp. 119-122.) (43/13 5954 Great Britain.)

It is shown that the down gust requirement in the strength specification is open to the objection that heavier loads may be taken by the front spar at lightly loaded weight than those for which the spar was designed. This is normally covered by the factor of safety of 2, but the method of calculating the loads on a basis of all-up weight is not very rational. Some available data concerning the magnitudes of down gusts are reviewed and the sharp-edged gust hypothesis briefly examined. The British requirement is compared with those of the I.C.A.N. and the U.S.A. The conclusions are that there are no very practical alternatives to sharp-edged theory and while the estimate of the magnitudes of normal down gusts at 25 f.p.s. appears satisfactory and British standards of strength in this respect need not be tightened up, a modification to the requirement to meet the above objection is desirable. A suggested alternative is put forward.

Aerial Fighting in Spain. (Les Ailes, No. 824, 1/4/37, p. 12.) (43/14 5446 Spain.)

Retractable undercarriages have led to a number of casualties since the mechanism is very vulnerable to gun fire. A pancake landing generally leads to the loss of the aircraft, even if the crew escape serious injury. The French

observer also is of the opinion that the bombers in use suffer from blind spots and lack centralised fire control. Wing guns are generally inaccurate, since the barrel is short and the mounting too flexible. In addition, the time lag of 0.2 to 0.3 seconds in the firing control mechanism introduces serious errors.

Lessons of the War in Spain. (A. Langeron, Les Ailes, No. 825, 8/4/37, p. 12.) (43/15 5536 France.)

The following conclusions are drawn:—

(1) The handling of modern single-seater fighter is much too complicated. In addition to the enemy, "the pilot has to fight his own plane."
(2) The principal aim of aircraft should be to inflict damage to the enemy on the ground (either against troops or buildings). For this purpose the raider must be fast. Douglas civil aircraft have been used practically without any modification, their superior speed enabling them to execute their mission whilst avoiding aerial combat.
(3) French military aircraft taking part in the fighting is definitely inferior to that of Italy and U.S.S.R.
(4) The tactics to be adopted in future aerial warfare are not yet settled. Large scale experiments are urgently required so that construction is concentrated on those types which are of use.

The Next Five Years in Spark Ignition Aviation Engines. (C. F. Taylor, J. Aer. Sci., Vol. 4, No. 3, Jan., 1937, pp. 113/116.) (43/16 5240 U.S.A.)

The following general predictions are made:—

1. Weight per b.h.p. should diminish to 0.75.
2. Cruising fuel consumption of the order of 0.35 lb./b.h.p. hr.
3. For high altitude work the liquid-cooled engine will come into favour.
4. Active development of the exhaust driven supercharger.
5. Special propeller designs for high altitude work will be investigated.

Measurement of Air Movement in the Interior of Diesel Engine Cylinders. (J. Geiger, Mitt. Forsch-Anst. Gutehoffmingshutte-Konzern, Vol. 4, No. 9, Nov., 1936, pp. 213-220.) (43/17 5495 Germany.)

A spindle carrying on the inside a radial blade with a pressure disc, and on the outside a mirror, movement of which is optically recorded, was inserted through the cylinder head. In the motored engine, without fuel, the air speed was measured for different positions of the induction valve mask and compared with that obtained by tangential induction channel without a mask. A graph shows the relationship between mask position, air speed at 80 mm. from the cylinder axis and fuel consumption. The latter is increased considerably (30 per cent.) at low air speeds, is approximately constant at average speeds (10-22 m./sec.) and increases somewhat at higher speeds (22-25 m./sec.).

Experimental Investigation on the Combustion in a Diesel Engine II. The Study of Combustion by Means of a Photo-Electric Cell and Emission Spectra. (G. Hamabe, F. Nagao and T. Watanabe, Trans. Soc. Mech. Eng., Japan, Vol. 2, No. 6, 1936, pp. 50-55. In Japanese-English Abstract, Phys. Ber., Vol. 18, No. 6, 15/3/1937, p. 484.) (43/18 5650 Japan.)

The combustion process in a two-cylinder Junker's Diesel engine has been investigated spectroscopically. A quartz window of 15 mm. diameter was inserted opposite the injection nozzle, and the light from it was allowed to fall on a photo-cell and the photo-current amplified. The result was registered on the same film as the pressure record obtained from the oscillograph of an electrical indicator. Examples of typical records (which are given in the paper) show that, during the course of a stroke, brightness and pressure curves rise similarly, the

curve of brightness rising more quickly at first than that of the pressure. From this the authors conclude that the combustion is at first localised in certain regions of the cylinder. It was also possible to determine that emission of light begins 15 mm. in front of the injection nozzle and spreads out suddenly from there. Changes in speed of revolution and load showed that light intensity increases with the load and that the commencement of light emission is delayed with decreasing load. Investigations with oils of different ignition quality showed that, when the ignition lag is great, combustion begins simultaneously in all parts of the cylinder, and is generally accompanied by knocking. By means of a quartz spectrograph and a rotating sector, the light emitted over 5° of crank angle was analysed. It was found that the bands associated with –OH and CH– radicals and C– atoms and present during combustion in a free atmosphere were missing.

Investigations on Knock Ratings I, II and III. (R. Kobayasi and S. Kajimoto, J. Soc. Chem. Ind., Japan, Vol. 38, No. 11, Nov., 1935, pp. 654-657B, and Vol. 39, No. 9, Sept., 1936, pp. 304-311B.) (43/19 5437 5472 Japan.)

Part I deals with the effect of tetraethyl lead on the knock rating of straight run and cracked petrols. In Part II, knock ratings were determined for two straight run petrols and their blends with alcohol, benzene and benzol, together with various amounts of lead. Part III extends the work to the lead susceptibility of mixtures of various pure hydrocarbons with straight run petrol. The work was carried out throughout on the C.F.R. engine.

The main conclusions were:—

1. The ethyl effect is much greater for straight run petrol than for cracked spirit using alcohol and benzol as blending agents instead of lead, the straight run petrol was again more susceptible in each case.
2. The lead susceptibility of straight run petrol is reduced by the addition of alcohol, benzene or benzol.
3. Experiments with pure hydrocarbons show that paraffins and naphthenes are more responsible to lead than aromatics and unsaturateds.

Evaluation of Motor Fuels. (A. W. Schmidt, Braunkohle, 1936, 35, pp. 535-48; J. Soc. Chem. Ind. Abstr. B., Vol. 56, March, 1937, p. 205.) (43/20 5438 Germany.)

By means of a microphone and oscillograph, knocking of motor fuels can be made visible on a screen. Diagrams show the average knock deflections of petrol and various fuel mixtures. If injected into the engine, fuels of low octane number can be used at considerably higher compression ratios than is possible when employing a carburettor. The phenomenon of vapour lock is discussed. Tables show the times taken for formation of 10 cc. of vapour from various fuel mixtures when passed through a narrow tube 1in. in length heated to 40-50°. Addition of 2 per cent. of various organic peroxides reduced the ignition lag of brown coal and bituminous coal tar Diesel oils.

Evaporation and Knock (of Motor Fuels). (O. Herstadt, Oel v. Kohle, 1936, 12, pp. 1014-5, 1111-4; J. Soc. Chem. Ind. Absts., B, Vol. 56, March, 1937, p. 205.) (43/21 5439 Germany.)

Apparatus for measuring the rate of evaporation of motor fuels at various temperatures is described and results are given for 17 fuels and pure substances. The evaporation times of mixtures of benzol, alcohol and petrol at temperatures up to 198° are plotted on triangular diagrams which enable the evaporation times of any ternary mixture to be read off. At low temperatures mixtures rich in benzol show the longest evaporation times, but at 184° and 198° mixtures rich in alcohol show a very much increased time, due to the formation of liquid drops surrounded by blankets of vapour. The effect of probable presence of liquid

drops during the combustion stroke on knocking is discussed. The abnormalities of evaporation shown experimentally are considered in relation to Callendar's theory of detonation and abnormal lead susceptibility at different temperatures.

The Mechanism of Formation of Engine Carbon in Internal Combustion Engines. (A. Maillard and W. Edelberg, Ann. Combustibles Liquides, 11, 1936, pp. 1117-1126; Chem. Absts., Vol. 31, No. 6, 20/3/37, p. 1981.) (43/22 5455 U.S.A.)

In order to eliminate the possible effect of the fuel on carbon deposition, an engine was operated on H_2 as a fuel, and the exhaust gas analysed to measure the combustion of the oil. Combustion accounts for only a small fraction of the total oil consumption, and used oil gave the same amount of engine deposit as fresh oil. With petrol as a fuel, the amount of deposit found was not very reproducible, and appeared to decrease when rich mixtures were used.

Conversion of Coal into Liquid Fuels by the Fischer Process. (F. Fischer, Petroleum Times, 36, 1936, pp. 613-614; Chem. Absts., Vol. 31, No. 6, 20/3/37, p. 1983.) (43/23 5456 U.S.A.)

Tropsch and Fischer (*cf.* C.A. 20, 2814) found that $(CO + H_2)$ at 400° and 100 atm. with alk. Fe catalyst produced oxygenated hydrocarbons. At lower pressures less O_2 combines. A catalyst was developed, active at 190° and 1 atm., producing the paraffinic hydrocarbons " Kogasin." Steam + CH_4 produce water gas containing one part CO to $2H_2$. The gas is caused to react over the catalyst with dispersion of heat, and the products are recovered by condensation and adsorption. The weight per cent. of products are: Gasol (light fractions) 8, motor spirit 62, Diesel fuel 24, paraffin wax 2 and ceresin 4, varying with operating conditions. The higher boiling motor spirit requires treatment to improve anti-knock properties; the Diesel fuel is of the best type.

The Ignition of Gaseous Mixtures by Hot Particles. (R. Silver, Phil. Mag., Vol. 7, No. 156, April, 1937, pp. 633-57.) (43/24 5527 Great Britain.)

Apparatus for measuring the lowest temperature at which a hot sphere will instantaneously ignite a gaseous mixture of known composition is described. The particle, heated in a furnace to the required temperature, is blown into an explosion chamber containing the mixture at normal temperature, the speed of the particle being kept as nearly as possible constant at about 4 m./sec. Attempts with methane air mixtures were abandoned on account of the high temperatures required, but a series of experiments was carried out with coal gas pentane and hydrogen air mixtures using a range of sizes of platinum and quartz spheres (0.109 to 0.500 cm.). Over this range the ignition point of a 10 per cent. coal gas air mixture fell from 1,140-855°C. with increasing particle size. For both coal gas and pentane air mixtures platinum and quartz spheres produced approximately similar results, but gave slightly differing results in the case of hydrogen air mixtures. In every case the minimum ignition point diminished rapidly with increasing size of particle, but even with the largest spheres used it still greatly exceeded the known ignition point of the mixture. The problem is discussed theoretically and an approximate form of theory suggested on the assumption that extinction is due to cooling by conduction to the unburnt parts of the gas. A relationship is worked out between sphere radius and sphere temperature which is satisfied when explosion only just takes place. The theory can only be used at present to predict qualitative results. It is discussed with reference to chain reactions.

Home Produced Motor Spirit. (Engineer, Vol. 163, No. 4240, 16/4/37, p. 449.) (43/25 5611 Great Britain.)

Replying to a question in the House of Commons, the Secretary for Mines recently said that the production of motor spirit by low temperature carbonisation was nearly 750,000 gallons in each of the years 1934 and 1935. In addition, the

production of tar and tar oils amounted to nearly 4,500,000 gallons in 1934 and over 5,000,000 gallons in 1935. Particulars for 1936 are not yet available. The production in 1935 by the hydrogenation of coal and tar oils (including some low temperature tar) was nearly 21,000,000 gallons of motor spirit, and in 1936 rather more than 33,000,000 gallons. No heavy oil was produced.

The Heat and Time Factors in Vapourisation in the Engine. (J. Small, J. Inst. Petrol. Techn., Vol. 22, Oct., 1936, pp. 706-25.) (43/26 5670 (G) Great Britain.)

An investigation of the vapourisation of petrol in air, on the basis of a diagram corresponding to the Mollier diagram for water, is described. Results in the form of formulæ, tables and diagrams, show that a high degree of vapourisation during induction is not necessary for ignition. Pre-heating of the air is probably much less effective in promoting vapourisation than heating the walls of the induction system, on which the petrol settles as a liquid film.

Factors Influencing Wear of Valve Seats in Internal Combustion Engines. (C. G. Williams, Engineer, Vol. 143, No. 3719, 23/4/37, pp. 475-476. Contd. from No. 3715, 26/3/37, p. 358—Abstract, A. and N., No. 42.) (43/27 5723 Great Bratain.)

Probably the most promising method for reducing seat wear is by the use of appropriate materials, of which there is a fairly wide choice. Heat-treated high-speed steel has much to recommend it, as it is machinable before heat treatment and is of reasonable cost. Stellite also gives excellent results and is widely used, though it is somewhat expensive. There are other materials almost as good. Monel metal is probably the best material for use in conjunction with aluminium cylinder heads. Measurements of exhaust valve temperatures at full load were taken on various car and lorry engines and show an appreciable effect of cylinder bore. Alcohol fuels give a reduction of exhaust valve temperature of the order of 50°C. on 800°C.

Motor Fuel. (Hungary Pat. 115,320, 2nd November, 1936.) (F. Timar, Chemical Abstracts, Vol. 31, No. 7, 10th April, 1937, p. 2410.) (43/28 5817 Hungary.)

Heavy hydrocarbons are saturated with a series of gases which respectively reduce knocking, accelerate combustion and improve ignition.

Examples are methane, acetylene and hydrogen. The absorption process may be carried out in the presence of Ni-Pd catalysts, MnO_2 and active carbon.

Preventing Separation of Solids and Semi-Solids from Liquid Lubricants in Internal Combustion Engines. (Siemens and Halske, A.G.B.P. 455, 790, 28th October, 1936; Chemical Abstracts, Vol. 31, No. 7, April, 1937, p. 2412.) (43/29 5818 Great Britain.)

Deposition of solid or semi-solid substances, *e.g.*, C, from organic lubricants is prevented by modifying the inner walls of I.C. engine cylinders by contacting them with S at 100-350°. Sulphur may be deposited by electrolysis of solutions (sulphides, polysulphides, thiocyanates, etc.) on to the surface, which is then subjected to high temperature; or the treatment may consist in contact with an organic lubricant containing free sulphur, with the walls at high temperature.

Operation of Internal Combustion Engines and Production and Supply of Fuel Thereto. (Ammonia Casale Soc. Anon., B.P. 460, 498, 15th July, 1936, J. Soc. Chem. Ind., Abstracts B, Volume 56, April, 1937, p. 322.) (43/30 5885 Great Britain.)

An ammonia-hydrogen mixture ($NH_3/H_2 = 3/19$) is used as fuel, the hydrogen being obtained by catalytic decomposition of 3 to 18 per cent. of the NH_3 in an apparatus connected to the engine and utilising the waste heat from the latter to heat the catalyst.

Automatic Power and Mixture Control (Pratt and Whitney). (Aeroplane, Vol. 52, No. 1354, 5/5/37, pp. 540-1.) (43/31 5952 U.S.A.)

The device described (known as the Eclipse Regulator) attempts to keep the density of the intake air at the carburettor jets constant and equal to its value at some predetermined altitude. For lower altitudes the intake air is throttled by a subsidiary device and the proportion of heated air adjusted so that although the main carburettor throttle is left fully open, both power and mixture strength remain constant at cruising value. For take-off and emergency, provision is made to strengthen the mixture by opening up additional jets. These jets are placed in parallel with the normal cruising jets and the fuel flow to them is controlled by oil operated poppet valves placed in the pipe line. Neither needle valves nor sealed float chambers are employed and the mechanism which operates the intake throttle through an oil servo motor is very robust.

Fuel of High Octane Number. (Inter. Avia., No. 425, 24/4/37, p. 4.) (43/32 5958 U.S.A.)

It is reported that Pan-American Airways are now using anilol to increase octane rating of their fuel from 87 to 94. Anilol is a mixture of alcohol, aniline and neutralising acids, the quantity required being about 6 cc./gallon. Anilol cannot be mixed with the fuel in the tank but is injected by means of a special automatic valve at the carburettor. An important characteristic of anilol is that it prevents icing up in the carburettor.

No detrimental effect on engine parts was observed after extended use.

A New Cathode Ray Oscillograph (Polar Co-ordinate and Uniform Time Scale). M. Ardenne, H.F. Technik, No. 4, April, 1937, p. 140.) (43/33 5868 Germany.)

The circular time scale is obtained by a combined electro-static and magnetic deflection. The time for one period can be regulated between 1×10^{3} and 0.5×10^{3} seconds, the accuracy being of the order of 0.5 per cent. The radial deflection is of the order of 0.4 mm. per volt. Details of the circuit are given.

Rotoroid Scales for Measuring Instruments. (H.F. Technik, No. 4, April, 1937, pp. 141-142.) (43/44 5869 Germany.)

The cylindrical scale is mounted on a flexible metallic tube, bent in the form of an arc over which the pointer moves. The flexible tube can be rotated about a stationary support and in this way different parts of the scale utilised. By inter-connecting the scale moving mechanism with the measuring instrument in such a way that changes in sensitivity and scale go together, troublesome magnification factors are avoided and at the same time the risks of damaging the instrument are considerably reduced.

Bending Tests of Circular Cylinders of Corrugated Aluminium Alloy Sheet. (A. S. Miles and others, N.A.C.A. Tech. Note No. 595, March, 1937.) (43/35 5590 U.S.A.)

Bending tests were made of two circular cylinders of corrugated aluminium alloy sheet. In each test failure occurred by bending of the corrugations in a plane normal to the skin. It was found, after analysis of the effect of short end bays, that the computed stress on the extreme fibre of a corrugated cylinder is in excess of that for a flat panel of the same basic pattern and panel length tested as a pin-ended column. It is concluded from the tests that light bulkheads closely spaced strengthen corrugated cylinders very materially. The section properties of corrugated sheet are summarised in an appendix.

A Theory for Primary Failure of Straight Centrally Loaded Columns. (E. E. Lunkguist and C. M. Fligg, N.A.C.A. Report No. 582, 1937.) (43/30 5591 U.S.A.)

Primary failure is defined as any type of failure in which the cross-sections are translated, rotated, or translated and rotated, but not distorted in their own

planes. For illustration, the theory is applied to a column of I section. The conclusions, however, are generalised to include any column with a cross-section symmetrical about its principal axes. When a column is attached to a skin, the great stiffness of the skin in its own plane causes the axis of rotation to lie in the plane of the skin. It is shown how the effective width of skin that may be considered to act with the column and how the bending stiffness of the skin resists twisting of the column and raises the critical stress. An illustrative example shows how the theory for a primary failure may be used to construct the column curve for a skin-stiffener panel.

The Hypothesis of the Secondary Structure Applied to the Mechanical Properties of Metals. (Dr. P. Duwez, Engineering, Vol. 143, No. 3719, 23/4/37, p. 461.) (43/37 5718 Great Britain.)

Numerous properties of crystals cannot be explained on the conception of a perfect geometrical network in which all the planes of the atoms of the same family are identical. The anomalies can, however, be explained if the existence of a secondary structure, such as defined by Zwicky, are admitted. The author considers that in a family of reticular planes of a crystal there exists a certain number of planes having properties different from those of the other planes and distributed at sensibly equal distances. The mechanical properties are directly influenced by the presence of these planes, and they can be used to explain the phenomena of work hardening and fatigue failure. The hypothesis of the secondary structure is still very controversial, but in the author's opinion it may render great service in increasing our knowledge of the properties of metals.

New Developments in the Flame-Proofing of Fabrics. (N. L. Deutsch, Rayon Textile Monthly, Vol. 17, No. 10, October, 1936, pp. 689-690, and No. 11, November, 1936, pp. 747-748.) (43/38 5827 U.S.A.)

After reviewing the various inorganic salts which have been in common use for the last 50 years, a new flame-proofing agent (trade name " Abopon ") is described. This substance is a complex inorganic boro-phosphate, in the form of a water-white liquid " resin." It is claimed that " Abopon " is superior to the common flame-proofers in that it does not develop acidity in the fabric nor does it lose its effectiveness in time due to crystallisation. Details of the strength of solution of " Abopon " required for the treatment of various fabrics are given and the tests for flame-proofness of the National Bureau of Standards (U.S.A.) are described. (Seven references.)

Theories of Age-Hardening. (The Metallurgist, 30/4/37, pp. 18-19.) (43/39 5870 Great Britain.)

In order to exhibit the phenomenon of age-hardening, the alloy must be originally in a state of thermodynamic instability. The resultant hardening is either due to a modification of the distribution of the solute atoms in the solute lattice (knot hardening) or actual precipitation may occur (precipitation hardening). In the case of knot hardening, the rearranged electrons, if suitably grouped, may cause an increase in electric resistance somewhat like light is scattered by particles, if the latter are of suitable size. In this way, ageing and changes in electrical resistance may go together. This is not, however, always the case and the theory has still to account for the great specific effect of small additions of certain elements on the age hardening of the resultary alloy.

Polished Surfaces. (The Metallurgist, 30/4/37, pp. 17-18.) (43/40 5871 Great Britain.)

The method of electron diffraction applied to the surface of liquid mercury shows the latter to be in an amorphous condition. Similar results are obtained when highly polished metal surfaces are examined (Beilby Layer), although in certain cases recrystallisation under the influence of the underlying material may occur.

It is hoped to extend the method of electron diffraction to the study of the initial stages of electron deposits and thus obtain new light on the problem of adhesion.

Ice Formation in the Atmosphere. (Don. McNeal, J. Aer. Sci., Vol. 4, No. 3, Jan., 1937, pp. 117/123.) (43/41 5241 U.S.A.)

The following general conclusions are drawn:—

1. Icing conditions may be expected in any form of cloud at a temperature of 2°C. or below.
2. The danger of icing conditions in regions above clouds is not great.
3. Ice may form in rain below a warm front provided the lower cold air has cooled the aircraft surfaces below 0°C.
4. Clear ice may be expected in clouds at suitable temperature where vertical currents sufficiently strong to support larger droplets are found.
5. Rime may be expected under similar conditions if the vertical currents are insufficient to support large drops.
6. It is misleading to attempt any correlation between icing conditions and type of cloud. This results from the difficulty of classifying and identifying the various types.

Study of the Light Diffused by Particles in the Air. (H. Grisollet, Comp. Rend., Vol. 202, No. 22, 2/6/36, pp. 1872-1874.) (43/42 5415 France.)

Diffusion of light by the dust in Paris air has been investigated at night by allowing a prismatic beam of parallel light to illuminate simultaneously a known thickness of air and a mat white diffuser, the latter receiving the light at a fixed angle of incidence of 45°. Photometric comparison of the relative brightness gives a ratio R characteristic of the diffusion. R was determined for values of the angle between the incident ray and the line of sight of 45°, 90° and 135°. Finally the proportion of polarised light in the diffused light and the number of dust particles were determined. The quantities $R\,(45)/R\,(90)$, $R\,(135)/R\,(90)$, and $R\,(45)/R\,(135)$, varied between 9 and 27, 0.2 and 0.7, and 13 and 90 respectively, results in sufficiently good agreement with Y. Rocard's theory. Between 0.12 and 0.42 of the light was partly polarised in the plane defined by the incident ray and the diffused ray. In general, diffusion increased with the number of dust particles present.

Theoretical and Experimental Studies of Convectional Circulation and its Relation to Land and Sea Breezes. (T. Kobayast and others, Aer. Res. Inst., Tokio, Vol. 12, No. 145, Feb., 1937, 67 pp. in English.) (43/43 5497 Japan.)

The motion developed in a fluid when one half of its base is heated has been solved mathematically, and the solution compared with some experimental results and with observed data on sea breezes.

Experiments were carried out on water in a tank, to which was given a temperature gradient corresponding to the potential temperature gradient of the atmosphere. The temperature of one half of the bottom of the tank was then raised a few degrees. Powdered aluminium was dusted into the water and photographic records were made of the elliptical circulation developed above the boundary of the warm and cold portions. Velocities of the water and the speed of growth of the circulation were measured. Experimental and mathematical results agree well provided that the effect of viscosity is taken into account and a suitable value given to the vertical variation in temperature. In the case of a sea breeze the mathematical solution gives the relationships between the rate of rise in temperature of the earth's surface by solar radiation and the wind velocities at various points and times, the height of the limit of the breeze and the speed of extension inland of the region covered by the breeze.

The Measurement of the Albedo of Artificial Fogs. (E. Regener, Zeitschrift f. Physik. Chemie., Abt. A, Vol. 139, 1928, pp. 416-424.) (43/44 5533 Germany.)

The albedo of a body is defined as the ratio of the light diffusively reflected (in all directions) to the incident light. The albedo of natural clouds has been extensively studied by Stuchtey and Wegener (see A. and N. No. 42, item 43). In order to carry out successful albedo measurements, with artificial fogs, the latter have to be very dense and the present paper deals primarily with the experimental production of such fogs. Three types of fogs were employed, the principal constituents being sulphur trioxide, ammonium chloride and paraffin oil respectively. In each case the density of the fog was artificially increased by using CO_2 instead of air. The fog formed a sharply demarcated layer at the bottom of a glass tank (1.2 × 1.4 × 1.1 m.). Above the layer was suspended a plaster of Paris plate and the whole illuminated by sunlight (altitude 30 to 60°). Comparative albedo measurements were carried out by means of a Marten's photometer placed vertically above the box, the results being in close proximity to unity for all the fogs tested. In all the albedo measurements it was noted that maximum readings could only be obtained if the air above the fog was clear of any diffuse fog layers. Such layers always tend to form in time, either by diffusion and on account of small thermal disturbances. A very dense fog is formed if ether is poured on a layer of liquid air. Unfortunately the resultant white fog is too unstable for accurate measurements, but the arrangement forms a most effective lecture experiment.

The Measurement of Upper Winds by Means of Pilot Balloons. (M.O. 396, Air Ministry, published by H.M.S.O.) (43/45 5703 Great Britain.)

At British meteorological stations, the ascent of the balloon is usually followed by one theodolite, the height of the balloon being obtained by assuming a constant rate of ascent (calculated from the starting lift). The results of many observations show that this method gives reasonably correct values of the upper winds in the majority of cases. The paper describes in detail how observations of this kind are carried out and reduced. At the same time a modification of the single theodolite method, the so-called tail method, is described, which consists in measuring the apparent length of a tail attached to the balloon as seen through the telescope of the theodolite. From the known dimensions of the tail the height can be calculated without making any assumption as to the rate of ascent.

Radio Meteorograph System. (Inter Avia, No. 420, 6/4/37, pp. 3-4.) (43/46 5942 U.S.A.)

A balloon 5ft. diameter carries a miniature radio transmitting set, batteries and a meteorograph in a balsa wood box 6 × 6 × 4½ inches.

The decreasing air pressure as the balloon rises causes a small switch arm to move over a set of contacts and operate the radio transmitter. Predetermined audio notes put an automatic recording gear on the ground into action. Other signals are sent out controlled by air temperature, humidity, and light intensity (clouds). The angle of elevation is estimated by a special wireless method and from the known height, the path of the balloon can be mapped.

Visit of French Aeronautical Engineers to the U.S.A. (Les Ailes, No. 827, 22/4/37, p. 8.) (43/47 5740 France.)

The following points struck the French observers:—

(1) The New York aeronautical exhibition was primarily a civil aviation show—only four military exhibits.

(2) Government laboratories carry out researches up to the point where the manufacturers can take over. New ideas, new materials and new methods of construction receive equal support.

(3) Constant speed propellers are favoured against independent (electrical) control of pitch.
(4) Direct injection of petrol for spark ignition engines is receiving considerable attention.
(5) In engine design, questions of reliability and mass production outweigh all others (maximum diameter or weight).

Long-Span Self-Supporting Steel Aeroplane Shed Roofs. (Houel, Sci. et Ind. (Travaux), Vol. 20, 1936, pp. 549-53. Engineering Abstracts, No. 73, April, 1937, pp. 32-3.) (43/48 5776 France.)

Steel aeroplane sheds ordered by the French Air Ministry and suitable for rapid construction, removal and re-erection are described. They are of 70 m. clear span, 66 or 55 m. depth with a height of clear opening of 10 m., and the principle adopted in their roof construction is that of the thin sheet of double curvature. The roof covering consists of self-supporting steel sheeting 1.4 mm. in thickness, in panels 10.2 m. by 4.7 m., stiffened at the edges by welded stiffeners. Full details are given of the supporting structure, the whole of which is assembled by bolting. The main framework for six sheds can be erected in 24 days. Three sides of the shed are closed by reinforced concrete walls 1.5 m. in height surmounted by steel sheets having large corrugations, the remaining side being closed by sliding doors manipulated by hand. The total weight of the shed including doors is 541 tons, or about 115 kg./sq. m. (23.5 lb./sq. ft.) of covered area.

Report of the N.A.C.A. for 1936. (Inter Avia, No. 413, 13/3/37, pp. 1-3.) (43/49 5777 U.S.A.)

Investigations regarding boundary layer control are only shortly alluded to in this year's report. Whereas the year before reference was made to the planned investigations into boundary layer suction to increase the maximum lift coefficient as well as to the adaptation of the same method to the reduction of drag, recent investigations were more especially concerned with boundary layer characteristics and various control methods. Investigation into effectiveness of chemical solutions to prevent ice formation on aeroplanes showed that the most effective ice inhibitor is a 7 : 1 mixture of alcohol and glycerine. An arrangement by which the liquid is fed through tubes to a porous leather covering enveloping the parts concerned means an additional gross weight of less than 0.5 lb./ft. of span, or about 50lb. for a transport aeroplane. The amount of liquid required varies with the type of ice formation; in wet clouds at low temperature, which constitute about 95 per cent. of the icing conditions, the formation of ice on a modern transport aeroplane can be prevented by about 1 gallon per hour; more severe conditions in ice storm regions may require as much as 5 gallons per hour.

Pacific Air Service. (Inter Avia, No. 420, 6/4/37, pp. 5-6.) (43/50 5943 U.S.A.)

The Pan-American Airways have so far carried out 94 successful crossings of the Pacific. The following procedure is adopted:—

The all-out power available (four Pratt-Whitney twin-row engines) is 3,800 b.h.p. On taking off, 90 per cent. or 3,420 b.h.p. are taken for 60 seconds. For the next six minutes, to gain altitude, 2,660 b.h.p. (70 per cent.) are developed. Following this initial climb, the engines are throttled to 2,090 b.h.p. (55 per cent.) to gain the flying height and the balance of the flight is carried out at 1,820 b.h.p. (48 per cent.).

The large amount of reserve power enables the aircraft to fly on three and even on two engines.

During the last two years, about 100 hours' practice flying were done on three engines and about 50 hours on two engines.

Air Traffic Regulations. (Inter Avia, No. 423, 17/4/37, p. 6.) (43/51 5947 U.S.A.)

The Department of Commerce has made the fitting of approved radio antenna compulsory on transport planes as from November 1st, 1937.

The design of this antenna has to be such as to eliminate as far as possible the static interference of rain and snow. So far four types have been developed: (*a*) Streamline body above nose of machine; (*b*) " ring in the nose " projecting from nose of machine; (*c*) rotatable ring below fuselage; (*d*) a type mounted inside fuselage.

As from January 1, 1938, all transport planes will have to be fitted with radio direction finders.

Short Wave Wireless Detector of Obstacles by Reflection (fitted to ss. " Normandie "). (U.S. Nav. Inst. Proc., Vol. 63, No. 409, March, 1937, pp. 439-442.) (43/52 5254 France.)

A special micro valve with antenna incorporated in the glass bulb is used to generate 16 cm. waves modulated at 7,500 cycles.

The valve is placed inside a parabolic reflector of 75 cm. aperture. A similar valve placed in a second reflector is used as receiver. The distance between emitter and receiver is 6 metres and when the wireless beam is reflected by an obstacle, the current detected is carried to an amplifier and is received on earphones or on a visual indicator. As soon as signals are detected, the two reflectors, which are normally revolving automatically through about 40° are stopped and precisely directed for maximum signal strength. From the known bearings and base line, the distance of the obstacle follows. It is stated that reflections from passing ships could be obtained up to distances of the order of 7 km. and that under favourable conditions readings can be obtained up to 20 km.

Modern Receiver Valves: Design and Manufacture (with Discussion). (M. Benjamin and others, J. Inst. Elec. Eng., Vol. 80, No. 484, April, 1937, pp. 401-439.) (43/53 5596 Great Britain.)

The authors discuss the main features in the geometrical design of the types of valve in common use to-day and the various factors, mechanical and chemical, which impose limitations in manufacture. The minimum tolerances to which it is possible to reproduce characteristics are indicated. The paper includes a brief historical survey of the recent improvements in thermionic emitters and gives details of the precautions necessary in the production of modern highly efficient oxide-coated cathodes and insulated heaters. Pumping and activation processes are described, and the main factors affecting the life of a valve are discussed. The last section of the paper deals with some of the limitations encountered in the use of valves, such as hum, microphony, noise, and frequency limitation, and the methods of minimising these factors are given. The authors conclude with some observations on possible future developments. Valves depending on secondary emission are being studied as well as valves depending on the deflection of an electron beam rather than on the control of electron density. (40 references.)

Ultra-Short Wave Propagation Along the Curved Earth's Surface. (P. von Handel and W. Pfister, Proc. Inst. Rad. Eng., No. 3, Part I, March, 1937, pp. 346-363.) (43/54 5704 U.S.A.)

The penetration of ultra-short wave radiation beyond the range of optical sight is dependent on the diffraction and refraction of the rays. Proceeding from an analogy to optics the diffraction is calculated by various methods. It is found that calculation of the ray distribution beyond the line of sight yields the best agreement with measurement. The practical application of the results of calculation is represented by curves which give the decrease of field intensity with distance for various elevations in the whole range of wave lengths at present of interest. The curves are substantiated by aeroplane measurements. Measurements of the influence of refraction are appended.

ABSTRACTS OF PATENT SPECIFICATIONS.

(Specially abstracted for the Journal by W. O. Manning, F.R.Ae.S.)

Abstracts of Patent Specifications received by the Society are published in the Journal. It should be noted that these abstracts are specially compiled by Mr. W. O. Manning, F.R.Ae.S., for the Journal and are only of those actually received and subsequently bound in volume form for reference in the library. These volumes extend from the earliest aeronautical patents to date, and form a unique collection of the efforts which have been made to conquer the air.

The Council accept no responsibility whatever for the accuracy of the abstracts and in any case of doubt the full patent can be consulted when necessary in the library of the Society.

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AERODYNAMICS.

462,205. *Improvements in Machines Travelling in the Body of a Fluid.* Oger, G., 27, rue Bodinier, Augers, Maine et Loire, France. Dated Jan. 30th, 1936. No. 2,870.

The proposed machine is not unlike a normal aeroplane in appearance, but the rear portions of the wing (in the case of an aeroplane) are adapted to receive a movement of vibration, and this portion then acts substantially independently of the front portion. It is stated that if the rear portion vibrates with a mean velocity greater than the speed of the relative wind the lifting power of the wing may be increased several times, while the drag is reduced. If the speed of vibration is lower than the wind speed, it is stated that the lift diminishes and the drag is increased.

437,885. *Improvements in or relating to the Streamline Formation of Bodies for Land Vehicles and Aircraft.* Tennant, W. J., 111/112, Hatton Garden, London, E.C.1. Dated March 1st, 1934. No. 6,605.

In the case of motor vehicle bodies and the like for which it is stated that it is not possible to use the most favourable aerodynamic shapes owing to practical considerations, it is proposed to counterbalance the bad shape by the delivery of pressure air at the points of disturbance, the air being tapped through conduits opening at zones of pressure on the body. Energy may be added to this air by means of fans, blowers, or the like, or the exhaust gases may be used.

AEROPLANES—CONSTRUCTION.

460,318. *Improvements in or relating to Aircraft.* Bonomi, V., Via Cappuccini 22, Milan, Italy. Convention date (Italy), Jan. 16th, 1935.

This specification claims a compound aeroplane comprised of two units, one power driven and one without an engine, the two being uncoupled during flight. The object of the arrangement is to facilitate the take-off of a heavily loaded aeroplane by reducing the wing loading at the time of starting.

462,390. *Improved Construction of Wings, Aerofoils and the like for Aeronautical Machines.* Mayrow, J. J., 35, Goldhurst Terrace, Finchley, London, N.W.6. Dated Aug. 29th, 1935. No. 24,138.

The construction proposed comprises upper and lower contour frames each composed of booms and ribs and the latter are so constructed and arranged that they provide a plurality of points of intersection located on the booms, whereby they form with the booms a meshwork disposed adjacent and conforming to the exterior contour of the structure, the upper and lower frames being connected together by posts jointed to the frames at points where the ribs and booms intersect.

462,539. *Improvements in or connected with the Construction of Aircraft, Bodies, Wings and Aerofoils.* Mayrow, J. J., 35, Goldhurst Terrace, Finchley, Middlesex, N.W.6. Dated Sept. 10th, 1935. No. 25,150.

It is proposed to use spars, ribs or skeleton framing for aircraft with a web of sheet or strip metal formed with central longitudinal corrugations and with transversely corrugated borders on opposite edges, the transverse corrugations being engaged with flanges on booms and secured thereto.

461,158. *Improvements in or relating to Folding-Wing Aircraft.* The Fairey Aviation Co., Ltd., Hayes, Middlesex, and Lobelle, M. J. O., Ludlow, 298, Langley Road, Langley, Bucks, and Voss, E., Badgercroft, 6, St. Anselm's Road, Hayes, Middlesex. Dated Dec. 20th, 1935. No. 35,332.

The wings are folded by turning each first about a horizontal axis and then about a vertical axis. There may be a fixed stub wing attached to the fuselage, the folding wings being attached to the stub wing. The foldable portion of the wing is carried by means of a cantilever which is rotatable relatively to the non-foldable portion, the cantilever being hinged at the junction of said portions. The foldable portion, when extended, is locked by strong pins passing through eyes on the respective portions. These eyes may be arranged on the circumferences of circles concentric with the cantilever, and it is desirable that common means should be provided for inserting the pins into, and withdrawing them from the eyes, and these means may be arranged to cause the pins to engage or disengage in succession.

457,309. *Improvements in or relating to Sheet Metal Walls and/or Partitions for Aircraft.* Dornier Metallbauten G.m.b.H., Friedrichshafen, Lake Constance, Germany. Convention date (Germany), June 29th, 1935.

It is proposed to stiffen sheet metal panels for aircraft by riveting to them flanged U-section members in which the flanges may be stiffened by means of small up-turned flanges. These members, where they cross, are joined by special cross-shaped fittings which are curved to fit the members, and the whole is fastened together with rivets. It is claimed that U-sectional members which are not of the same height or shape may be jointed in this manner.

457,428. *Improvements in or relating to Doors, Panels, or other Covering Elements.* Thornton, A. A., 7, Essex Street, Strand, London, W.C.2. Dated Feb. 11th, 1936. No. 4,113.

It is proposed to construct doors, etc., of paper rendered rigid by treatment with bitumen. The door is formed of two members spaced from each other, the space between consisting of corrugated material, round tubes packed together, or similar means, the whole being glued together. An outer covering of three-ply may be glued on.

459,793. *Improvements in or connected with the Construction of Aircraft Bodies, Wings and Aerofoils.* Mayrow, J. J., 36, Goldhurst Terrace, Finchley, London, N.W.6. Dated July 11th, 1935. No. 19,870.

This specification refers to spars formed of metal strip in which the web of sheet metal is formed with a series of alternate transverse tapering corrugations, the taper running towards a neutral axis of the web, and in most cases crossing such neutral web, the crests of the corrugations of the upper and lower edges of the web being engaged with curved shape or like longitudinal corrugated metal strips or flange members.

458,985. *Improvements in and relating to Aircraft having Detachable Cantilever Wings.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7. Dated July 3rd, 1935. No. 19,068.

The wing is shown in the diagram as being carried above the fuselage by narrowed extensions of the fuselage bulkheads. Across the top of these extensions there is a pair of plates which can be fixed to plates on the wing roots by four pins. A rocking lever operates the ailerons by means of pins fitted in its extremities. These engage slots in bell cranks attached to the wings, which former are wired to the ailerons to increase the ease of dismantling.

458,751. *Improvements in and relating to Aircraft having Variable Incidence Wings.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7, and E. D. Abbot, Ltd., Farnham, Surrey. Dated April 22nd, 1936. No. 11,493.

In aircraft of the type in which the incidence of the front plane is variable by the pilot for the purpose of control, it is proposed to balance the normally unbalanced rear portion of the wing by means of a weight attached to a lever connected to the pilot's control. It is stated that in this way a lesser weight is required than if the weight is attached to the leading edge of the wing because of greater leverage.

458,789. *Improvements in or connected with the Construction of Aircraft Wings.* Vickers (Aviation), Ltd., Pierson, R. K., and Bewsher, J., all of Weybridge Works, Byfleet Road, Weybridge Surrey. Dated June 27th, 1935. No. 18,409.

In aeroplane wings constructed on the stressed skin principle it is stated that normal methods of construction either involve projecting parts which increase drag, or else difficulty in removing parts when repairs are necessary. It is proposed, therefore, to construct such a wing with the lower flanges of the ribs detachable and fixed to the lower skin. The skin with the rib flanges is then put in position and attached by means of screws.

462,856. *A Safety Device for Aeroplanes.* Martin, J., Higher Denham, Uxbridge, Middlesex. Dated Dec. 11th, 1935. No. 34,383.

This is a device intended to protect the pilot in the event of a low wing monoplane turning over on to its back while landing. It consists of a sort of slot mounted on a post which can be extended sufficiently to protect the pilot. The post is fitted in the vicinity of the cockpit. Fluid pressure may be used to extend the device.

462,904. *Improvements in Spars for the Wings of Aircraft.* Vogt, R., Oderfelderstrasse 13, Hamburg 37, Germany. Dated Sept. 14th, 1935. No. 25,549.

The spar proposed consists of two approximately semi-circular shells, the abutting edges of which are overlapped by cover strips. The cross-sectional shape may be such that there is more material present at the points of maximum bending stress than at the points subjected to lesser stresses.

AEROPLANES—UNDERCARRIAGES.

462,963. *Improvements in Tail Skids or Tail Wheels for Aeroplanes.* Saulnier, R., 5, rue de Monceau, Paris, France. Convention date (France), Nov. 9th, 1935.

It is stated that in normal skids the angle of the skid to the ground varies in use, and that this is objectionable. It is therefore proposed to use a device arranged so that the skid or wheel moves parallel to itself when deflected. In order to attain this the skid tube is supported by a system of levers which constrain it to a parallel motion.

AIRCRAFT—GENERAL.

461,669. *Improvements relating to Apparatus for Signalling from or for Display Purposes in connection with Aircraft.* Rangabe, A. R., 5/11, Theobald's Road, London, W.C.1. Dated Aug. 17th, 1935. No. 23,148.

It is proposed to provide a method of towing an advertising device consisting of a flexible banner sign, without the necessity of carrying it in the packed condition and also without the necessity for an undesirably long towing rope. A loop of rope is attached to the article to be picked up and is arranged with a length detachably connected to, and stretched between a pair of vertical supports, so that the article can be picked up by means of a hook attached to the aeroplane.

461,318. *Improvements in Aeroplanes or Flying Machines.* Beadon, R. R. & C., The Glen, Valley des Vaux, St. Helier, Jersey. Dated Aug. 10th, 1935. No. 22,616.

The aeroplane proposed has planes in front of and behind the centre of gravity, the planes consisting of superimposed surfaces backwardly stepped, the number of planes aft exceeding the number forward. It is stated that such an arrangement corrects automatically any tilt of the machine.

459,639. *Improvements in Aeroplanes de Rougé.* C.R.A.M., 7, Cité Martignac, Paris, France. Convention date (France), May 11th, 1935.

This aeroplane has normal wings but is characterised by the fact that the stabilising and controlling surfaces are carried a considerable distance above the wing by a streamlined support. Rudders may be placed at the lower rear end of the support. A twin-engined machine is described having two sets of stabilising surfaces and two supports.

459,895. *Improvements in and relating to Aeroplanes.* Cairns, A., 67, Easton Road, New Ferry, Birkenhead. Dated July 19th, 1935. No. 20,574.

It is proposed to produce a difference of pressure on opposite sides of a rotary disc, by furnishing one side of the disc with a centrally placed projecting tubular ring between which and the outer edge of the disc rearwardly sloping radial vanes or forwardly sloping aerofoil projections are provided and in which outer edge rearwardly sloping auxiliary vanes set with their roots transverse to the disc edge and with their free rear edges spaced out from the disc edge may be provided.

457,281. *Aeroplane or Glider of the Rigid All-Wing Type.* Canova, F. P., Via Mario Giuriati 4, Milan, Italy. Dated May 24th, 1935. No. 15,236.

This specification describes an aeroplane having a wing of rhomboidal form which it is claimed has advantages over circular or square wings. It is stated that the large chord near the fuselage has advantages as it can contain all the aeroplane fittings.

AIRSCREWS.

460,149. *Improvement in Gearing for Airscrews.* de Paravicini, T. P., The Old Manor, Abbots Inn, Andover, Hants. Dated July 19th, 1935. No. 20,601.

This specification is concerned with a variable gearing for aircraft engines arranged so that the variable pitch airscrew rotates faster under take-off conditions. The gearing described is of the planetary type controlled by clutches which may, in turn, be controlled by hydraulic mechanism. There is claimed a means for varying the pitch of the airscrew blades and a single controlling member connected to the gear and the pitch controlling mechanism which in one position secures fine pitch and high speed, and in another position a coarser pitch and lower speed.

461,010. *Improvements in and relating to Propulsive Systems for Aircraft.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7. Dated Aug. 8th, 1935. No. 22,448.

It is proposed to use at least two lateral airscrews carried by a hollow stub wing projecting at each side of the fuselage and to which the main wing is attached. Each propeller is driven by a central power plant through any suitable gear fitted in the stub wing. The airscrews may be pushers.

460,707. *Cellular Airscrew Propeller and the like.* Crutchley, G. G., 15, Bridge Street, Haverfordwest, Pembrokeshire, South Wales. Dated July 3rd, 1935. No. 18,987.

It is proposed to make propeller blades which are composed of cells. These cells are cavities bounded by a rib or vein of metal or suitable substance built with their axes at the required angle of incidence in the case of a fixed pitch wing and movable as a whole in their lateral plane in the case of a variable pitch wing.

BOMBS AND BALLISTICS.

462,483. *Improved Gun Mountings for Aircraft.* Hiscocks, S. W., Oakland, Belvedere Road, Coventry, and Hughes, H. A., Westfield, 74, Plumstead Road, Norwich, Norfolk. Dated Oct. 30th, 1935. No. 29,912.

It is proposed to provide a frame mounted vertically in an aeroplane fuselage, capable of rotation. At the top and at the bottom of this frame there is a gun mounting so that one gun fires above the fuselage and the other below. The upper gun is capable of being elevated from about the horizontal, and the lower gun is capable of being depressed from about the horizontal, but the guns are trained in unison.

CONTROL OF AEROPLANES.

461,157. *Improved Mechanism for Actuating the Control Surfaces of Aircraft.* The Fairey Aviation Co., Ltd., Hayes, Middlesex, and Youngman, R. T., Walcot, Church Crookham, Aldershot, Hants. Dated Dec. 13th, 1935. No. 34,641.

In order to overcome difficulties experienced in operating the flaps of large aircraft, it is proposed to use a flap which can be lowered bodily from the retracted position to a point below the wing by a lever which is pivoted at its front end on the aircraft wing, and which is part of a link and lever mechanism comprising said lever, a second lever parallel therewith and also pivoted at its front end on the aircraft wing and a link connecting the free ends of said levers, said second lever and said link together constituting a toggle or knuckle-jointed strut the elements of which, when the flap is moved to its lowered position, are straightened out to form one side of a triangulated structure, a second side of which is formed by the first lever, and the third side of which is constituted by the wing structure between the pivotal axes of the first and second levers.

462,382. *Improvements in or connected with Flying Machines.* Back, W. E., Mancroft Towers, Oulton Broad, Suffolk. Dated 7th June, 1935. No. 16,560; 7th Feb., 1936, No. 3,753; and 26th Feb., 1936, No. 5,806.

The aeroplane described is a heavily staggered tandem monoplane having ailerons on both wings. These can be moved differentially for banking, or the ailerons on each wing may be moved in opposite directions for control in pitch. They may also be moved together for altering the camber of the wings. Flaps may also be provided. There are a number of claims for operating gear.

462,498. *Improvements in or relating to Means for Controlling Aircraft.* The Fairey Aviation Co., Ltd., Hayes, Middlesex, and Youngman, R. T., Walcot, Church Crookham, Aldershot, Hants. Dated March 28th, 1936. No. 9,295.

The device described is a form of flap which consists of a small auxiliary aerofoil mounted below and to rearward of the main wing. It is stated that when this auxiliary aerofoil is set at small angles, it gives an increase of lift, while at large angles, when its leading edge may be in contact with the main aerofoil, it acts as a split flap.

462,272. *Improvements in or relating to Aeroplanes.* Passat, H. J. B., 10, Victoria Avenue, Surbiton, Surrey. Dated July 8th, 1936. No. 18,983.

It is proposed to use a front elevator instead of the more usual tail plane elevator. This elevator is fitted in front of the aeroplane wing and in close proximity to it, and it is stated that its aspect ratio is to be at least four.

461,353. *Oscillation Vibration Damper for the Mechanism Controlling the Movable Flaps of Aeroplanes.* Bechereau, L., 2, Rue Gervex, Paris, France, and Carronee, R., 1 rue Vauvenarques, Paris, France. Convention dates (France), Jan. 30th, 1935, and May 24th, 1935.

This apparatus is intended to absorb vibrations in the control mechanism of aeroplanes by means of shock absorbers in the control mechanism. The method consists in interposing in the steerage control a rectilinear vibration damping apparatus of the piston and cylinder type, in which the piston rod extends on opposite sides of the piston through the braking cylinder, and which exerts a symmetrical action in both directions, the resistance of this apparatus depending solely on the frequency of the oscillations of the flaps.

457,454. *Improvements in and relating to Aircraft Controlling Surfaces.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7. Dated May 25th, 1935. Nos. 15,328 and 15,329.

This specification describes a readily detachable aeroplane tail plane which can be fitted to the fin rather than to the rear end of the fuselage; the former position is claimed to have advantages. The tail plane, of normal construction, is fixed to the fin by pins inserted in suitable fittings, and the elevators are driven through a pin and slot arrangement by a short transverse shaft at the rear, so that detachment and replacement are facilitated.

459,691. *Improvements in and relating to Aircraft having Single Span Wings of Variable Incidence.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7. Dated 22nd April, 1936. No. 11,492.

This specification refers to an aeroplane which is controlled by the variation of incidence of the front plane of two planes in tandem. This front plane is of cantilever construction and is supported above the fuselage by two outrigger structures extending laterally and upwards, the apices of which carry the plane,

and are hinged to allow control movements. Struts connect the rear spar of the plane to the pilot's control stick.

459,730. *A Manner of and Means for Controlling an Aeroplane, Glider, or the like Flying Machine.* Blaker, H., 59B, Ekbalpore Road, Kidderpore, Calcutta, Bengal, British India. Dated Aug. 26th, 1935. No. 23,903.

The arrangement proposed consists of a flap operating from a position just under the leading edge of the wing. When folded this flap conforms with the normal aerofoil outline. It is claimed that the arrangement may be used for lateral control, as an air brake, and that it induces an upward pressure on the leading edge of the wing, causing the front of the machine to rise, thereby facilitating recovery from a nose dive.

456,863. *Improved Devices for the Automatic Control of Camber Flaps and the like for Aeroplanes.* Société d'Inventions Aeronautiques et Mécaniques S.I.A.M., 1, Route des Alpes, Fribourg, Switzerland. Convention date (France), April 5th, 1935.

The operation of the flap is done by a hydraulic device consisting of a cylinder, one end of which is connected to a fluid pump, the other to a normal hydro-pneumatic accumulator. A piston in the cylinder is connected to the flap via a piston rod and link. The flap is kept in the down position by means of the compressed air acting on the fluid in the accumulator, the pressure being transmitted to the cylinder. When it is desired to raise the flap, pressure is produced on the other side of the piston by means of an engine-driven pump. As the flap is kept down by air pressure, excessive force on the flap will result in a reduction of angle.

456,969. *Improvements in and relating to Aircraft and Particularly Aeroplanes.* Percival, E. W., 20, Grosvenor Place, London, S.W.1. Dated March 14th, 1935. No. 7,914.

It is proposed to operate wing flaps by means of a manually operated lever connected by a link with a toggle joint through which the flap operation is effected. The lever is fitted with a ratchet and also has a separate arm attached to a spring. This arm is so placed relative to the spring that the spring action becomes greater as the flap is forced farther down, so that the spring force approximately balances the flap force over the working range.

457,114. *Improvements in and relating to Brake or Landing Flaps and other Control Surfaces for Aeroplanes.* Irving, H. B., the National Physical Laboratory, Teddington, Middlesex. Dated May 21st, 1935. No. 14,786.

This is a flap device so designed that the air forces on the flap may be wholly, partially, or over balanced as desired. The flap consists of two or more portions one section of which is pivotally connected on an axis located between its forward and rear edges with a drag rod extending to a point on the aeroplane and pivotally connected with a second point on the aeroplane so that motion imparted to the further section about its pivotal connection with said point will move the first mentioned section away from the general surface of the wing or aerofoil with which the flap or control surface is associated into a position in which the air stream will subject it to forces tending to move its opposite edges in reverse senses about the axis of its connection with the drag rod.

458,887. *Improvements in or relating to Flying Controls for Aircraft.* The Blackburn Aeroplane and Motor Co., Ltd., Seaplane Base, Brough-on-Hull, East Yorks, and Cramshaw, A. H., 4, East Mount, Ferriby, East Yorks. Dated Dec., 31st, 1935. No. 36,055.

This arrangement provides a means for an automatic trimming of an aeroplane control and consists of an operating lever mounted in the control surface which is capable of some freedom of movement relative to the surface. This lever is

connected to a tab. A dashpot is fitted so that the relative movements depend on the setting of the dashpot.

460,841. *Improvements in and relating to Motion Transmitting Mechanisms Adopted, for instance, for the Actuation of the Control Surfaces of Aeroplanes.* Ellis, D. L., National Physical Laboratory, Teddington, Middlesex. Dated May 3rd, 1935. No. 13,282.

The object is to provide a servo control which is self-locking against flutter but not against normal operation. The control member is arranged in driving connection with a worm driving a worm wheel rigidly connected with the control surfaces, so that a definite correlation between the displacement of the servo surface relative to the control surfaces and the displacement of the main control surfaces from its neutral position is secured. The wind force tending to restore the servo surface into its neutral position with respect to the control surface is applied in the rotation of the worm in a direction to assist in the restoration of the control surface also into its neutral position.

460,636. *Aeroplane Stabilising Means.* Gray, W. E., 8a, Bank Parade, Edgware, Middlesex. Dated Aug. 1st, 1935. No. 21,810.

It is proposed to increase damping in roll in the region of the stall and of damping at angles above the stall by providing the upper surface of the wing with a fin or fins near each wing tip. The fins may be parallel or skewed and they extend over the greater portion of the chord and they are of greater height towards the rear. The action of these fins is stated to be in the interception of outward air currents which are stated to exist on the upper surface of a wing when it is stalled.

DE-ICING.

462,570. *Improvements in Fluid Pressure Devices for Aircraft and Other Purposes.* Dunlop Rubber Co., Ltd., 32, Osnaburgh Street, London, N.W.1, and Wright, J., of the Company's Works, Fort Dunlop, Erdington, Birmingham, Warwickshire. Dated Dec. 30th, 1935. No. 35,942.

This is a de-icing arrangement of the type which prevents ice formation by expelling liquid over the wing. The liquid is here expelled in a positive manner through a series of apertures, and there is a hollow member containing a distensible tube, which, by distending, expels fluid from the member. The outer member may have apertures which operate as valves operating under low pressures, and it may be made of rigid or non-rigid material.

458,862. *A New and Improved Method of and Means for Preventing the Formation of Ice on Aircraft.* Van der Horst, H., 22, Alexanderlaan, Hilversum, Holland. Dated June 26th, 1935. No. 18,248.

It is stated that if the leading portions of an aeroplane wing are covered with polished sheet chromium, ice will not form. It is stated that the surface tension of water on polished chromium is less than on any other material so that the water forms drops on the surface and is blown away before it has time to freeze.

ENGINES.

461,169. *Improvements in Mounting Devices for Aircraft Engines and Analogous Purposes.* Martin, J., Martin's Aircraft Works, Higher Denham, Uxbridge, Middlesex. Dated June 22nd, 1936. No. 17,362.

It is proposed to provide means for mounting engines so that they are firmly secured in position and in alignment, and so that they may be easily dismounted. Two hollow or tubular members are adapted to be carried by the engine and mounting, and internal coupling members adapted to be secured between the

hollow members and means for effecting a locking action between the coupling member and one of the hollow members, the arrangement being such that the internal coupling member and said means are withdrawable axially thereof through one at least of the hollow members so that they may be uncoupled.

430,002. *Improvements in and relating to Power Transmission Couplings.* Strandgren, C. B., 14, rue Gallieni, Versailles, Seine et Oise, France. Convention date (France), Nov. 26th, 1932.

This specification describes a form of universal coupling comprising two discs, one driven and the other driving, which are disposed adjacent to each other. The driving disc carries two equal-sized chain wheels connected with a chain symmetrically disposed with reference to its centre. The other disc carries two pins. Each of the chain wheels carries a slot and the two slots are maintained parallel with each other by the chain. The pins engage the slots and transmit the drive. Several alternative arrangements are shown embodying a similar device.

462,682. *Improvements in or relating to Multi-Cylinder Internal Combustion Engine Units.* Scott, B. D., Churn House, Churn, Berks. Dated Sept. 12th, 1935. No. 25,372.

The proposed engine has two sets of cylinders arranged horizontally on each side of the crankcase. Each set of cylinders operates its own crankshaft which are geared together so as to rotate in opposite directions. It is claimed that the arrangement provides a perfectly balanced engine, and that the forces of torque reactions may be annulled.

460,075. *Improvements in and relating to Aircraft Engines.* Baynes, L. E., 144, Cromwell Road, South Kensington, London, S.W.7. Dated Aug. 7th, 1935. No. 22,340.

This specification relates to cooling arrangements for aircraft engines, and it is proposed to provide a rearwardly facing outlet for the cooling air in the trailing portion of the wing immediately in front of a pusher airscrew. The air inlet being arranged in the under surface of the wing adjacent to the part to be cooled. There may also be louvres or scoops.

FUELS.

460,843. *Improved Method and Means for Effecting Transfer of Fuel Containers, Persons, or the like from One Aircraft to Another during Flight.* Atcherley, R. L. R., Fulford Villa, York. Dated June 4th, 1935. No. 16,025.

It is proposed to provide both the "cow" and the "calf" aircraft with means for trailing a line so that when they are flown on parallel courses with approximately similar speeds the lines will trail at a large enough angle to each other for intersection and engagement. Engagement is caused by one aircraft moving across the flight path of the other, after which one line is used to heave the other. One may have a grapnel and the other a stop.

462,818. *Improved Method and Means for Effecting Transfer of Fuel, Containers, Persons, or the like from One Aircraft to Another during Flight.* Atcherley, R. L. R., Fulford Villa, York. Dated Feb. 18th, 1936. No. 931.

This specification describes a method of refuelling a "calf" aeroplane from a "cow" aeroplane in flight. The cow aeroplane has a pipeline and the calf aeroplane has a heaving line of which a part is connected to the pipeline. The calf's line is passed over a pulley or the equivalent and the lee part of the line is pulled away from the calf by a drogue, so the cow's line is pulled in towards the calf by the drag of the drogue.

INSTRUMENTS.

458,812. *Improvements in Apparatus for Facilitating Blind Flying.* de Florey, L., 19, Rector Street, City County and State of New York, U.S.A. Convention date (U.S.A.), July 5th, 1934.

It is stated that as the sense of hearing is instinctively associated with the matter of direction the act of steering can be naturally governed by aural indications and that in this way blind flying can be made a more natural and instinctive process. It is proposed to use, in combination, binaural signal receivers, a signal source for said receivers, means sensitive to change from a predetermined normal flying attitude and means controlled by said flight attitude, sensitive means for selectively impressing signal from said source on said binaural receivers in accordance with deviation from said predetermined flight attitude and for creating a neutral signal indication in both receivers under said predetermined normal flying attitude conditions.

MISCELLANEOUS.

457,075. *Improvements in or relating to Propelling Devices for Watercraft and Aircraft.* Blicharski, F., Schekaneder-gasse 2, Vienna VI, Austria. Dated Nov. 20th, 1935. No. 32,199.

Gear for fin-like or wing-like propelling devices working oppositely in pairs wherein the carrier arms of each pair of wings are fitted on two oppositely running parallel shafts which are coupled to common sliding frames or parts, pistons or the like, reciprocated symmetrically with respect to the shafts characterised by each shaft being so coupled in like manner with two sliding frames or the like reciprocated in opposition by a common drive that there are obtained two gear sets similar to each other and running symmetrically opposite to each other.

PARACHUTES.

460,114. *Improvements in or relating to Parachutes.* Popelakova, M., Hladkov 701, Prague XVIII, Czechoslovakia. Convention date (Czechoslovakia), June 12th, 1935.

It is proposed to secure parachutes in a pack on the body of the airman comprising one or more connecting members to which the rigging lines of the parachute and the ends of the supporting belts are attached, the connecting members being so secured to the frame of the pack or to the pack itself that they readily become detached therefrom upon the opening of the pack and the parachute. Thus it is possible to use a single type of parachute which may be attached either to the chest, the back, or the seat of the airman with one and the same harness.

462,559. *Improvements in or relating to Parachutes.* Pool, Z. H., Flight Lieut., R.A.F., Henlow Camp, Bedford. Dated Oct. 3rd, 1935. No. 27,321.

The parachute described has a canopy incorporating an air vent, and means whereby the effective area of such vent is gradually increased automatically by the deployment of the canopy, and after reaching a maximum is gradually reduced by the approach of the canopy to complete deployment. Means may be incorporated by which the vent can be influenced manually.

462,670. *Improvements in and relating to Parachutes.* Nonaka, S., 2079, Taketacho, Naoiri-gun, Prefecture of Oita, Japan. Dated Sept. 10th, 1935. No. 25,165.

This specification describes a parachute intended to permit the wearer to control at will the rate of descent. The parachute has a central escape port with a mov-

able annular wall forming its edge, and the port can be reduced or increased in area by means of a group of cords actuating the said annular wall.

462,071. *Improvements in and relating to Parachutes.* Nonaka, S., 2079, Taketacho, Naoiri-gun, Prefecture of Oita, Japan. Dated Sept. 10th, 1935. No. 25,166.

The parachute described is intended to open promptly with the minimum shock. It has an adjustable escape port, a number of cords for adjusting the size of the port, a central suspension cord connected to the operating cords, a fixed ring suspended near the escape port, a floating ring under the fixed ring, a number of shroud cords, etc.

462,722. *Improvements in and relating to Parachutes.* Nonaka, S., 2079, Taketacho, Naoiri-gun, Prefecture of Oita, Japan. Dated Sept. 10th, 1935. No. 25,167.

It is intended to produce a parachute which opens promptly, accurately, and smoothly when in use. The parachute body has a number of small holes and a number of pocket flaps or resistance members secured to its back along the periphery near the point of attachment of the suspension cords, each of such flaps forming a pocket with its lower edge free, a resident member being secured to the lower free edge of each of the said pocket flaps and a short cord being provided for limiting the degree of opening of each of the said pockets.

459,222. *Improvements in Parachutes.* Szalay, G., Beniczky utea 10, Matyasfold, Hungary. Dated April 1st, 1935. No. 10,128.

It is stated that known parachutes open with about 30 per cent. reliability and that this specification describes a parachute which opens with complete reliability. The parachute proposed is smaller in diameter than usual and is of multiple formation. In order that as large a resistance as possible may be offered a limited way of escape through the parachute is provided through vents. Reliability in opening is obtained with a ring which may be connected to the innermost part of the parachute sheet by pivoted arms.

ROTOR CRAFT.

461,170. *Improvements in and relating to Aircraft.* Konig, J., Smetamvonameste 6, Makr Ostran, and Kadlec, J., Prevoz No. 683, Makr Ostran, Czechoslovakia. Convention date (Czechoslovakia), June 29th, 1935.

This aircraft has rotating supporting surfaces of screw-shaped form arranged one above the other rotating in opposite directions and at different speeds. The surfaces consist of curved rods or tubes which are fitted into hubs, a number of these hubs being secured one above the other and driven by toothed gearing.

460,634. *Improvements relating to Aircraft.* Kay Gyroplanes, Ltd., and Kay, D., both of 18, Atholl Crescent, Edinburgh, Scotland, and Dyer, T. W., Durie, New Road, Netley Abbey, Southampton. Dated July 31st, 1935. No. 21,761.

It is proposed to arrange that the rotor mast is mounted in such a manner that when the member is tilted the point of support of the member is moved relative to the aircraft with the object of keeping the centre of lift of the rotor system in substantially the same position to the centre of gravity or with the object of varying the position of the centre of lift relative to the centre of gravity by any predetermined amount.

SEAPLANES.

463,008. *Improvements in Means for Absorbing Vibration in Aircraft.* Short Bros. (Rochester and Bedford), Ltd., and Robinson, G. I., both of Seaplane Works, Rochester, Kent. Dated Feb. 11th, 1936. No. 4,117.

The device is described as used for a wing tip float which is supported by nearly vertical struts cross-braced by two wires, and the device is inserted at the crossing of the wires. As variable loads affect the device, shock is absorbed by means of rubber blocks.

458,905. *Improvements in and relating to Aircraft Landing Sails.* Kraft, E., and Kraft, R., Sogestrasse 23, Bremen, Germany. Convention date (Germany), June 6th, 1935.

The sail (so called) proposed refers to a sailcloth surface towed behind a ship so that it can act as a support for an aircraft, taking, when in use, the shape of the aircraft floats, and, thereby providing dynamic support. It is stated that the projection of the spreaders normally used cause turbulent flow of the water and cause difficulties in operation. It is proposed to overcome this by using spreaders of steel strip so that there is practically no projection. It is stated that with this construction the sail can adapt itself smoothly to the floats and to the continuously changing form of the water surface.

UNDERCARRIAGES.

460,316. *Improvements relating to Undercarriages for Aircraft.* Dowty, G. H., Arle Court, Cheltenham, Gloucester. Dated Oct. 12th, 1935, No. 28,234, and Nov. 14th, 1935, No. 31,582.

This specification is concerned with retractable undercarriages for aircraft and describes means by which in such chassis the extension of the chassis can be effected even if it fails to extend owing to technical difficulties, broken pipe lines, etc. The means proposed for this purpose is a spring which is used as a reservoir of energy, which energy can be utilised for extending the chassis if the normal mechanism fails, or the source of energy may be a compressed air reservoir and a valve arrangement may be used for cutting off from the jack the normal pressure supply and connecting it to the reservoir.

REVIEWS.

THE THEORY OF THE PROPERTIES OF METALS AND ALLOYS.
By N. F. Mott, M.A., F.R.S., and H. Jones, Ph.D. Published by the Clarendon Press. Price 25/-.

The engineer knows very little about the materials he uses. It is possible to measure such things as Young's modulus and tensile strengths in testing machines, and to form some idea of the crystal structure of metals by etching polished surfaces, but this information can only be interpreted in terms of practical experience, and the molecular reason for the engineering properties of materials remaining unknown.

It is impossible to foretell in what way the properties of a given metal may be varied by alloying it with others, and the effect of this and of heat treatment in varying the strength can only be found by testing. Hardness, resistance to corrosion, strength at high temperatures, and all other useful properties have been developed in metals by methods which depend on trial and error, and it is a tribute to the work done by metallurgists in spite of the absence of any theoretical knowledge, that we have the excellent structural materials that are available to-day.

The progress of engineering depends essentially on the improvements of materials. It is doubtful whether, even with our present knowledge, a better battleship than the " Victory " of Nelson's time could be designed and made, assuming that only the structural materials in use at that time were available; and, although progress in detailed design, methods of jointing, etc., is always going on, it is only new and improved materials which can lead to a large advance in the design of machines. It is unknown what possibilities remain to be exploited in the properties of materials, but it can be stated with certainty that improvement can only be slow in the absence of theoretical knowledge, and that, when the reasons for variations in properties are understood, it may be possible for the engineer to design the material out of which his structure is to be made, at the same time as he designs the structure itself, so that each is appropriate to each other.

The particular branch of physics which will lead to results of this type are dealt with in this book, but the subject has not been sufficiently developed to enable mechanical properties to be explained, still less predicted. Electrical conductivity, light reflection, magnetic properties and certain other matters such as specific heats have received explanations which depend on the properties of the molecule as interpreted by the theories of wave mechanics, the understanding of which depends on the student forgetting all he ever knew about the subject of classical mechanics. No attempt has yet been made to explain mechanical properties, and the matter is hardly referred to in this book, but that those who are working on this subject will eventually be able to add largely to our knowledge of this subject cannot reasonably be in doubt. When it is possible to predict with accuracy the mechanical properties of a new alloy, it is probable that materials greatly surpassing those in use to-day will be made available.

The present work is divided into seven sections. The first two deal with the thermal properties and electrons in equilibrium in the crystal lattice, and the third on motion of electrons in an applied field. Section four covers the important subject of cohesion, the beginning of the investigation as to the why and wherefore of strength. Unfortunately very little work has been done in the very field of interest to aeronautical engineers, the light alloy. Section five

deals with the crystal structure of metals and alloys, and the last two sections with the heat capacity and magnetic properties of the metallic electrons and the electric resistance of metals and alloys.

The work and theory described are the preliminary and difficult first stages for obtaining, what every metallurgist wants, some rules which will enable him to predict the engineering qualities of metallic alloys. Atomic physics has not yet reached that stage when the most important prediction of all, the probable strength of an alloy, can be made, though there are evidences already that there is some hopes the problem may be solved.

AERODYNAMICS.

By N. A. V. Piercy, D.Sc., M.Inst.C.E., M.I.Mech.E., F.R.Ae.S. Published by the English Universities Press, Ltd. Price 30/-.

This book contains an account of modern aerodynamical theory in a form which is convenient for the designer as well as for the student. The subject is dealt with competently and thoroughly. Starting with an account of the properties of air, there is a discussion on balloons and this is followed by a chapter on air flow at the end of which there is a thorough treatment of Reynolds numbers.

There is then a chapter on wind tunnels followed by one on aircraft in steady flight, and continued by more theoretical discussions on irrotational flow, vortices, wing theory, skin drag, etc., and the book is completed by final chapters on airscrews, performance and efficiency and safety in flight.

A book of this type was badly wanted and this one is probably destined to become the standard English work on the subject. Dr. Piercy has the gift, probably developed through long experience with teaching, of explaining complicated subjects in an intelligible manner. He also does not hesitate to admit that certain matters are, at present, beyond analysis, and it is not the least important attribute that such limitations of knowledge are clearly defined.

To the designer, the last chapter in the book is of particular importance. The author's detailed analysis of the performance of aircraft, in the light of modern knowledge, especially with reference to variations of Reynolds number, is particularly valuable. There is also an interesting discussion on stability in which the Gates method of graphical analysis is introduced, which is followed by a discussion on load factors.

One point of interest in the book is the development of approximate formulæ which can be used without serious error in place of the more exact and complicated forms. Mathematical complication in aeronautics has been growing for many years, and this tendency still continues, and there is a risk that in the future the designer may have to be so much of a mathematician that he may not have mental room for other matters of equal importance. If formulæ can be simplified and at the same time give results which are sufficiently accurate for practical design a most useful step will have been taken. It must be remembered that the resistance of a modern clean aeroplane may be varied considerably by matters over which the designer and mathematician have no control whatever, such as a shower of rain, dust, or a shower of gnats, met with as the machine is taking-off, would cause a serious deterioration of efficiency. In fact it would seem that the ideally smooth and polished aeroplane cannot exist outside the shop in which it is built.

This is a most important and valuable book which should remain the standard practical work on the subject for some years to come.

WAR ON GREAT CITIES.

Frank Morison. Faber and Faber. 1937. 8s. 6d. net.

There is much speculation as to exactly what will happen in the next war, especially to the civilian population. There is a theory that the coming of the

aeroplane will change all present ideas of warfare, that fundamental tactics will no longer be fundamental. It is to be regretted that those in aviation, in the army or in the navy, express such decided and often violent opinions of the value and power of the new arm, that they often destroy their own case and the confidence of those who are critical by over statements.

The greater part of "War on Great Cities" is given up to the actual facts of the results of air raids on London. Many photographs are given of the destruction caused and of many personal details of the raids. Two tables are given at the end of the book on the effects of incendiary bombs and explosive bombs dropped on London between May, 1915, and May, 1918.

A total of 354 incendiary bombs were dropped; of these 339 failed to cause any casualties, seven caused injuries only, and eight fatal injuries. Of the 567 explosive bombs dropped, 349 caused no casualties, 74 injuries only, and 144 fatal injuries. The figures are taken from the Fire Records of the London County Council and are for the Administrative County of London. The figures for the Metropolitan Police District, a considerably larger area, were greater. The total damage was estimated at £2,046,614. Altogether there were eighteen aeroplane raids and eight Zeppelin raids, 26 in all. Few places of importance were struck, and none which vitally affected the services, transport or administration of London.

Viewed in a cold historical light, with a knowledge of the progress which has been made since 1918 in speed, range and bomb-dropping power of modern aircraft, the prospects are appalling. But a hundred times the above figures would not put London out of action. The real thing which will matter will be the fall of one bomb on a particularly vital area of communication, and that will be an element of luck which no one can foresee.

It is difficult to predict the attitude of the population under intensive bombing, but it is not unlikely that the ordinary man in the street will adopt more or less quickly a fatalistic attitude which will certainly not lead to a wholesale flight from London. The attitude of the population in Spain is significant.

Intensive bombing of the civilian population, by its very horror, may well serve to stiffen the population to an extent which would make defeat far more difficult.

This is a book which is well worth reading and studying. The author's concluding words are worth quoting.

"Posterity will say to us that, despite the brilliant achievements of our age, we remained bunglers and barbarians at heart. We were the heirs of all the ages; yet we summoned from the ether a power which we had neither the wit nor the moral fibre to control."

CORRESPONDENCE.

To the Editor of the JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY.

Dear Sir,—I should like to be permitted to comment upon Dr. Desch's most interesting paper on Magnesium Alloys, lately presented to the Royal Aeronautical Society. I am able to comment on this paper only in so far as it concerns the working properties of the wrought alloys, and anything that follows should not be taken as having application to castings in any form.

I should like first to pay tribute to Dr. Desch's review of the existing knowledge on the working properties of magnesium and its alloys, and particularly on the very clear statement of the technical results arising from the hexagonal crystal structure of magnesium. When Dr. Desch deals with the wrought alloys, with

respect I must protest that there is something to be said for a material having a low elastic modulus, provided, also, that it is light. Suppose, for a moment, that a stressed part, *e.g.*, in bending, is to be designed in Elektron and in Duralumin solely upon the value of Young's modulus in each case, and suppose further, that a satisfactory stressing in Duralumin for this hypothetical case is given by a circular section 6in. in diameter. On the basis of Young's modulus alone the corresponding diameter in Elektron would be 6.75in. This can be so, and still give a weight-saving to the advantage of the magnesium alloy of about 16 per cent., but, remembering the factor for the modulus of the section, this value in the case of the magnesium alloy is 60 per cent. greater than in the Duralumin section. This represents simply increased stiffness, and I suggest that 60 per cent. increased stiffness, gained with a weight-saving of 16 per cent., is a condition of the greatest possible value in aircraft construction.

As one who has had some experience with the alloys mentioned by Dr. Desch which contain aluminium, silver, cadmium, and so on, added for the purpose of improving the tensile properties, I must mention what I believe is a serious limitation to their practical application. Undoubtedly the improvement in mechanical properties as compared with pure magnesium by the addition of these elements is remarkable, but experience with alloys containing aluminium and silver, whether in conjunction with cadmium or not, is that the enhanced mechanical properties are obtained only at the expense of corrosion-resistance. Indeed, I have not yet known a silver-containing alloy which can be satisfactorily pre-heated in an ordinary muffle furnace without producing copious oxidation, usually sufficient to prevent any subsequent forging at all. It is only proper to say that, in respect of these alloys, the National Physical Laboratory recommendation is that they should be pre-heated for forging in salt baths, but when it is remembered that salt bath heating necessitates a quench or partial quench to remove the salt before any forging process can commence, it will be clear that there is here a serious limitation to the application of this type of alloy in practice.

With regard to the figures which Dr. Desch gives as being obtained from propeller blades forged in the press and without heat-treatment, the tensile properties are excellent, but the fatigue range seems rather surprisingly low. In an airscrew forging made from the Elektron alloy AZ855, which had in the butt a 0.1 per cent. proof stress value between 10 and 12 tons per square inch, a maximum stress of 19/20 tons per square inch, and an elongation of about 8 per cent., a fatigue range of plus/minus 9.0 tons per square inch was lately obtained in tests conducted by the Royal Aircraft Establishment. One wonders, therefore, whether, in the case which Dr. Desch quotes, alloying has gone somewhat past the point where the natural high damping capacity of magnesium is effectively employed. The point is of interest, because airscrew blades in Elektron have been flying for years, in which the proof and maximum stress figures were much lower, and the fatigue range was equal to or higher than those figures quoted by Dr. Desch. This rather defines the problem on magnesium alloys, which is not simply to increase the tensile properties, but to do so without proportionately decreasing the damping capacity (*i.e.*, the high hysteresis value) of magnesium and without impairing a corrosion-resistance not strikingly good to begin with.

Yours faithfully,

S. J. NIGHTINGALE.

The 615th Lecture to be read before the Royal Aeronautical Society since its foundation on January 12th, 1866.

PROCEEDINGS.

A meeting of the Society was held at the Royal Society of Arts, John Street, Adelphi, London, on Thursday, January 28th, 1937. In the chair, Mr. H. E. Wimperis, President.

The PRESIDENT: Dr. de Bruyne was going to speak on a subject which was very much in their minds though little in their discussions in the Society hitherto, viz., plastic materials for aircraft construction. Dr. de Bruyne was well qualified to speak on this subject as he had made a special study of it. He was a Cambridge man who had taken the Natural Sciences Tripos and had worked for some years under Lord Rutherford. He was a Fellow of Trinity College, Cambridge, and had duties in respect of that college. Nevertheless, he had managed to be able to spend time in studying the particular subject of the lecture that evening and, in addition, had actually built an aircraft rejoicing in the name of " Snark " which was purchased by the Air Ministry, perhaps because of its attractive name, and this machine had since been used for aeronautical research at Duxford by Professor Jones and the staff working under him.

PLASTIC MATERIALS FOR AIRCRAFT CONSTRUCTION.

By N. A. DE BRUYNE,* M.A., Ph.D.,
Fellow of Trinity College, Cambridge.

SUMMARY.

INTRODUCTION.

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Thermosetting Resins.
Chemical Constitution of Bakelite.
The Manufacture of Bakelite.
Future Possibilities.
The Physical Structure of Bakelite.
Behaviour of Bakelite under Compression.
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* Director of Aero Research Limited.

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Introduction.

An account that is to be of any value of a subject in such an early stage of development as the use of synthetic resin materials in aircraft construction, must necessarily contain a great many first thoughts and rough guesses, and anyone writing such an account must be prepared to take the risk of having to eat his words at a later date. But I believe it is better to have blundered than never to have thought at all, and it is my hope that what I have to say will at least arouse interest enough among those with special knowledge to contribute to the discussion at the end of the lecture.

The study of the mechanical behaviour of synthetic resins is largely the study of the properties of matter in an amorphous state. In contrast to that of single crystals, which has attracted so much interest and been so productive of results in recent years, our knowledge of matter in its most extreme polycrystalline form is meagre. Practically all that we have we owe to Professor L. Prandtl (a name more familiar perhaps in connection with concepts such as the boundary layer and induced drag) who, by differentiating between true hysteresis and elastic after-effect (1), and by devising a mechanical model (2) of a molecular system capable of behaving like an amorphous material, has given us at least a satisfactory basis for discussion.

Our work at Duxford has been largely concerned with practical problems and, despite the need, the urgency of day-to-day requirements has made it difficult during the past year to give as much attention to fundamental research as we should have liked. It is therefore with real gratitude that I have to thank the Department of Scientific and Industrial Research for making us a grant (beginning from last October) which will enable some research to be done into the nature of things without regard to immediate utility.

It has been my privilage to work in co-operation with the de Havilland Aircraft Co., Ltd., and Messrs. Bakelite, Ltd., on the development of variable pitch propellers, but, since I was not associated with that development before it had reached an advanced stage, I should not like to be given credit for any considerable part of it. I mention this particularly because I am afraid newspaper reports may have given a contrary impression. Actually it is Mr. E. P. King and Mr. C. D. Philippe who have done the lions' share of the work and it is Mr. C. C. Walker who has been responsible for its direction.

It is a pleasure to acknowledge the help I have received in the preparation of this lecture from the staff of Aero Research, Ltd., and particularly from Dr. R. E. D. Clark, Mr. H. Leaderman, and Mr. G. Newell.

Part I. Properties.

Thermoplastic and Thermosetting Resins.

I suppose that the property of resins which first attracts attention is the possibility of moulding them into intricate shapes. In addition to this property common to all resins, some kinds of synthetic resins and to a limited extent one natural resin (shellac) have the valuable characteristic of being " thermosetting," *i.e.*, when once moulded they set to permanently infusible products. Most resins are " thermoplastic," *i.e.*, they become soft whenever the temperature exceeds a certain value. It is thus convenient to divide all resins into two classes—the thermosetting class and the thermoplastic class.

The thermoplastic resins are not of great interest for structural purposes, because although it might be possible for the softening temperature to be so high as to be above anything likely to be reached in service, it would in turn necessitate the use of an uncomfortably high moulding temperature; in fact, none of the thermoplastic resins appears to have a sufficiently high melting point for structural purposes. Two thermoplastic resins, cellulose acetate and methyl methacrylate, are, however, widely used in aircraft for windscreens and fairings.

This division of resins into thermoplastic and thermosetting classes is a fundamental one because the two classes are formed in different ways. Thermosetting synthetic resins are essentially condensation products formed by linkages between molecules with the elimination of water, while thermoplastic synthetic resins are polymerisation products formed by the simple process of joining up similar molecules as pearls are strung on a thread. In the condensation products, cross linkages take place as well as chain linkages. The process of growth by polymerisation is a common one in nature, and whereas for some reason or other our synthetic polymers stop growing after a certain chain length is reached, nature is able to grow much longer chains such as the cellulose micelle and the gigantic genes found in the salivary glands of Drosophila flies, which are actually visible under a microscope. Nature evidently uses catalysts to prevent the process of "Steric Hindrance" (3) which keeps down the sizes of synthetic chains and which makes the synthetic products so weak. Thus whereas most synthetic resin products consist of a chaotic tangle of comparatively short macro-molecules, chromosomes are flat ribbon-like structures of enormous size but probably not more than one or two molecules thick. Each part of this structure appears to be able by means of the surface electric charges set up by changes of hydrogen ion concentrations to select its own kind of unit from the surrounding medium and then when the hydrogen ion concentration changes again, to leave another ribbon of molecules juxtaposed and ready for further combination (4). The catalysts used by nature are apparently far more specific in their action than any of the catalysts with which we are familiar in inorganic chemistry. Their synthesis would put into our hands tools of a most powerful kind.

Thermosetting Resins.

There are two main groups of thermosetting resins (1) the phenol formaldehyde group (2) the urea formaldehyde group. All synthetic resins are weak in tension and need reinforcement. The best reinforcement on a strength-to-weight basis is cellulose, and it is an unfortunate fact the urea formaldehyde resins have an affinity for cellulose which results in a brittle structure. This affinity is so marked that it is believed that a chemical compound is formed for which the name " Glucanure " (5) has been suggested. This property, though useful in making crease-resisting cotton goods, is disadvantageous for structural purposes. Such resins have also a somewhat higher density than the phenol formaldehyde

group. From the manufacturing point of view they have the great attraction of being water soluble in their initial stages, and the expense, unpleasantness, and danger of working with organic solvents is absent.

Although not at present of direct structural importance, the urea formaldehyde resins, by the addition of suitable retarders and catalysts, can be made into excellent cements. These cements, because of their great strength and water resistance, are valuable for plywood manufacture, and can also be used in a cold setting form in general wooden aircraft construction. Unlike casein cements, they are proof against the attacks of mould and fungus.

In this lecture we will be concerned with phenol formaldehyde resins only. I propose for convenience to refer to such resins as "Bakelite," though I know that in so far as the word is a trade name its use in such a way is objectionable; but it has the merit of doing honour to Dr. Baekeland and of being known already to many of those here.

THE CHEMICAL CONSTITUTION OF BAKELITE.

Phenol and formaldehyde interact to form resinous products whose properties vary considerably with the conditions under which the reaction takes place. Analogy with well-known substitution reactions (such as that of a halogen in acetanilide (6) or of the phenyl diazo-group in aniline) (7) suggests that formaldehyde will attack phenol in two ways simultaneously

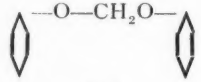
(I)

and ortho- and para- HO. C_6H_4. CH_2OH

(II)

producing a phenol ether (I) and a hydroxyphenylmethanol (II). (II) will not readily undergo further change but (I) will easily hydrolyse back to its progenitors. These will react again to give a mixture of (I) and (II) and (I) will be hydrolysed once more. In this way, given infinite time, the whole of the product may be converted into (II) but whether or not this will occur in fact will depend upon the various reaction rates involved and in the time allowed for the condensation.

In addition to these simple derivatives the diphenyl di-ether (III) and the three isomeric dihydroxy-diphenyl methanes (IV) may be formed in a similar way to (I) and (II). Again it is to be expected that a mixed ether-aryl methane (V) will be formed as a by-product in the formation of (IV).



(III)

HO. C_6H_4. CH_2. C_6H_4. OH

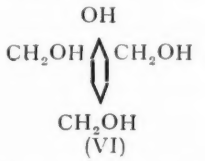
(IV)

HO. C_6H_4. CH_2. O. C_6H_5.

(V)

If the formaldehyde is in excess then this will be able to attack the benzene nucleus in more than one position and a large number of further compounds will result of which phenol trimethylol (VI) is an example. So far, experiment is in accordance with theory since most of these compounds have been isolated from the

reaction mixture. In addition there are others (such as VII) (8) for which it is not so easy to account.



(VI)

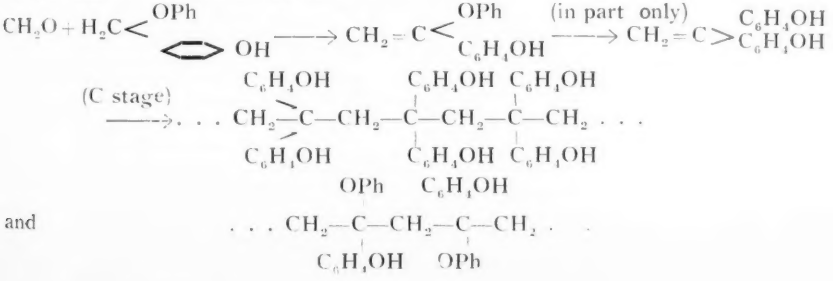
(VII)

It might be supposed that the substances actually formed would be largely determined in an easily predictable manner by conditions such as the relative proportions of phenol and formaldehyde. But unfortunately this is not so. In acid solution, for instance, equimolecular proportions of phenol and formaldehyde react rapidly until all the phenol and one half of the formaldehyde have disappeared and thereafter the reaction goes on more slowly, suggesting that compounds of types (III) to (V) are formed under such conditions. Clearly then the main reactions depend upon the relative speeds with which different groups of compounds are attacked, and even though the probability of the molecular collisions necessary for the formation of one compound is low, this particular compound may be formed if the rate of its subsequent interactions is large. In such a wild scramble for the pancake it is difficult to predict from initial conditions alone who will be the winner.

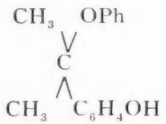
This all too brief account of the beginnings of the reaction will at least indicate the obscurity surrounding the formation and constitution of these resins. How the compounds initially formed combine to form macro-molecules is even more obscure. In what follows two of the better known theories will be briefly reviewed.

(1) During the formation of a phenolic resin there are, as Baekeland pointed out (9) three main stages to be distinguished. In the first or (A) stage a liquid or pasty product is obtained. Further heating produces partial polymerisation, and a (B) stage is reached in which the product is thermoplastic and swells in solvents. With further heating some varieties of the (B) stage resin give a (C) stage in which the true bakelite, unaffected by heat or solvents, is formed.

Baekeland found that in the transition from (A) to (B) water is eliminated, *i.e.*, condensation takes place, but that in going from (B) to (C) no loss of water occurs, so that probably the change is one of polymerisation. The evidence is perhaps hardly convincing in the light of our present knowledge of the properties of colloids, because if the molecular weight is large in the (B) stage the transition to macro-molecules might take place by condensation and the water could be absorbed in the molecular interstices. If, however, the (B) to (C) transition is one of polymerisation, then in view of the evidence that polymerisation is peculiarly apt to occur when ethylenic bonds are present, Baekeland and Bender (10) suggested the following mechanism.



According to this theory the use of a ketone (*e.g.*, acetone) to give a compound such as VIII

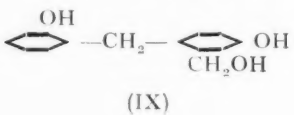


(VIII)

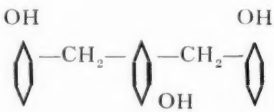
should prevent the formation of the (C) stage after treatment with formaldehyde. But in fact (VIII) does give a (C) stage resin. Quinonoid formulæ have also been invoked in order that ethylenic formulæ may be used, but they do not seem very plausible.

In brief, every attempt to explain the formation of bakelite in terms of the polymerisation of substituted ethylenes appears to be open to serious objections, and it seems that despite the attractions of the theory, ethylenic compounds may have no part in the reaction.

(2) The possibility remains that bakelite in its final or (C) stage is the result of a true condensation and not a polymerisation. A mechanism of this nature was suggested by Raschig (11) and although based on little sound experimental evidence at the time it has steadily gained in favour in recent years. Raschig believed that the Novolac resins consisted of various isomerides of type (IV). These by themselves were incapable of further condensation but on treatment with formaldehyde (*e.g.*, by heating with paraformaldehyde) they yielded alcohols of which (IX) is one of the many possible isomerides.



(IX)



(X)

These isomerides then reacted with phenol or with themselves to give compounds such as (X) after which the molecule could grow indefinitely by successive reactions of the same kind. Raschig's final formula for the (C) stage was an elaborate polycyclic structure, not free from objections from a stereochemical point of view, yet much research has tended to support his views on the fundamental stages of the reaction.

The relevant literature is so voluminous that a critical account of the experimental evidence in support of Raschig's theory cannot be given here. This would in any case be unnecessary as other reviews are available (12). But one recent confirmation is well worth mentioning: Megson (13) in an important paper (which also gives references to earlier work) has analysed the products obtained by the dry distillation of the resins and has shown that they are in accord with theoretical anticipations. He finds moreover that the resins obtained by acid and alkaline condensations do not differ in any fundamental way.

The molecular constitution of these resins may therefore with some confidence be pictured as follows:—During the transition from the (B) to the (C) stage, an immense number of benzene nuclei become linked together by methylene groups. Such linkages take place both in the ortho- and para- positions; the evidence as to which preponderates is conflicting. In this way chains are built up, and there can be little doubt that the formaldehyde attacks the ends of the chains more easily at first than at other positions where they are better protected sterically. But later the proportion of chain ends becomes small and the formaldehyde begins to attack the chains along their length; cross linking occurs and the chains become

joined together. These cross linkages are responsible, as Staudinger (14) has shown in the case of the polyvinyl benzenes, for the enormous resistance to chemical attack which is shown by thermosetting resins.

We may therefore imagine the structure of bakelite in the (C) stage to be something like that shown in Fig. 1 (15). The structure will in reality of course be three dimensioned.

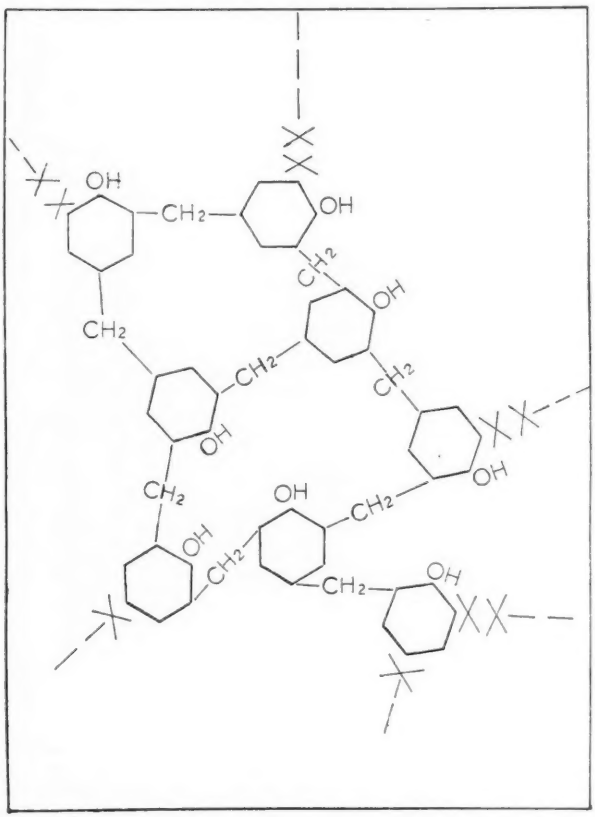


FIG. 1.

Suggested structure of bakelite.

THE MANUFACTURE OF BAKELITE.

The manufacture of bakelite, as will be gathered from the above discussion, is an empirical process whose success depends upon the exact control of temperature, concentration, time of reaction and the like.

Condensation is carried out either with acid or with alkali catalysts, and may be done either in one or two steps. In the " one-step " process, phenol and formaldehyde are heated with ammonia in a steam jacketed digestor to a temperature of 80° to 90° for about half an hour; as the reaction is exothermic careful control of the temperature is necessary. The reaction is complete when all the free formaldehyde has disappeared; water is then removed by vacuum evaporation. The one step process though simple is not very controllable, and it

is usual not to allow resins produced by this process to go further than a comparatively low state of polymerisation or condensation, so that they take some time to change to the C form. A slow setting resin is advantageous when it is to be used for impregnating fabric or wood as it gives time for impregnation to take place and the process is much better controlled.

When quick setting resins are required the " two-step " process is used, as in this process the product can be taken much nearer to the C stage without danger of reaching it. In the " two step " process the formaldehyde is added in two stages; the second charge is not added until the initial reaction has been completed and excess water removed. Usually an acid catalyst is used in the two-step process while an alkali is used in the single step process. Cresol is frequently used instead of phenol as it is cheaper, though the resulting resins are not as strong as the phenolic products.

If the resin is to be used for impregnating fabric, it is dissolved in methylated spirits to form a varnish; if it is used for making moulding powders it is ground and mixed in a rolling mill with fine sawdust (woodflour) and catalysts and lubricators.

Future Possibilities.

In reviewing our knowledge of the formation and constitution of the phenol formaldehyde resins the impression left on our minds is one of our ignorance and inability to control the reactions. The final C stage appears to be a muddled pattern of consequent low strength, very different from the orderly arrays of atoms or molecules found in cellulose or the proteins.

If we could orientate the molecules so as to increase the number of secondary links or van der Waal's forces we should be able to improve the mechanical properties. We can carry out such an orientation by mechanical means on many substances. Thus artificial silk (which is regenerated cellulose in which the micelles are irregularly arranged, in contrast to natural cellulose, in which they lie side by side) (16) can be much improved in strength if it is swollen in water or acid and then stretched; the experiment is easily carried out with a strip of cellophane. Regenerated natural silk can be improved in the same way (17). Vinyl acetate synthetic resins can be drawn into threads whose strength is increased by stretching after softening by heat. Of particular interest is the recent work of Carothers and van Natta (18), who have found that there is a definite relation between the lengths of molecules and their ability to be drawn into threads; a product of small original strength was in this way given a strength of 8.3 tons per sq. inch.

All attempts to improve the properties of bakelite in this way have been fruitless (15). Bakelite in its initial and in its final state of condensation has been drawn into threads and rolled and pressed without affecting its properties or its X-ray diagram, and it seems probable that the micelles are spherical in shape. This is confirmed by measurements of the viscosity of bakelite in solution (19, 20). Polystyrene, a thermoplastic polymerisation product, although known to consist of long chains of molecules, also refuses to undergo molecular orientation, probably because polystyrene in bulk has a tangled " cotton wool " structure (15).

But it is not impossible that some orientation could be achieved during the early stages of the reaction between phenol and formaldehyde by the use of electric fields. Adcock (21), for instance, has recently confirmed the results of earlier workers, that changes in the viscosity of common liquids such as acetone can be produced by electric fields; also long molecules such as p-azo oxyanisole have been shown to orientate themselves under such conditions (22). Knaggs and Schryver (23), have found that in gelatine solutions coagulated by electric fields, the " non-amino " nitrogen was increased, thus suggesting ring closures. Woods (24) has been able to orientate wool cells and rebuild them into a macro-structure by electric fields.

In a recent patent (25), it is claimed that condensation of phenol and formaldehyde can be effected in alternating fields without the use of catalysts. It is not therefore too much to hope, that we may obtain some control of the molecules in thermosetting resins so as to obtain products without reinforcement of a strength equal to that of cotton or silk.

THE PHYSICAL STRUCTURE OF BAKELITE.

If an X-ray analysis be made of bakelite by the Debye Scherrer method, photographs such as those shown in Fig. 2 (reproduced by kind permission of Dr. Houwink of the N. V. Philips Gloeilampenfabrieken, Eindhoven) are obtained. That on the left is of phenol formaldehyde in a low state of condensation, while the other photograph was obtained with the final product. Apart from an increase in the sharpness of the halo there is no difference between the two. The diameter of the ring corresponds to a diffraction spacing of 4.6 Angstroms; benzene and phenol give diffraction rings of the same diameter. Exactly similar results are obtained with a solution of B stage resin in acetone. From these photographs,

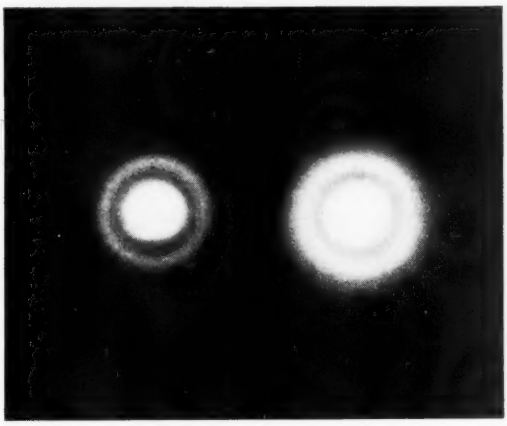


FIG. 2.

X-ray positives of phenol formaldehyde resin, in a low state (on the left) and a high state (on the right) of polymerisation.

it can at once be deduced that bakelite is a completely amorphous material, and that the chains of molecules cannot be arranged according to any regular plan.

The work of R. Houwink (15) has made it extremely probable that phenol-formaldehyde resins (at least in their initial stages of condensation) are "isogels"; that is to say, consist of a "sponge" whose pores are filled with the resin in a less condensed state. We have not space here to describe the numerous and exhaustive investigations (15) which point to this conclusion, but mention should be made of the work of Filon and Harris (26), who, from investigations with polarised light, have deduced that glass has a binary structure, one part being in a state of compression and the other in tension.

As condensation takes place the proportion of solid in the isogel increases, but it is improbable that the material ever becomes a complete solid, because even in fully hardened resins it is easy to detect the presence of free phenol. The strength and modulus of elasticity increase with the degree of condensation; R. Houwink (27) states that in the A stage the strength is about 13 lbs./sq. in., and E (determined by bending) is about 0.41×10^6 lbs./sq. in., while in the C stage the

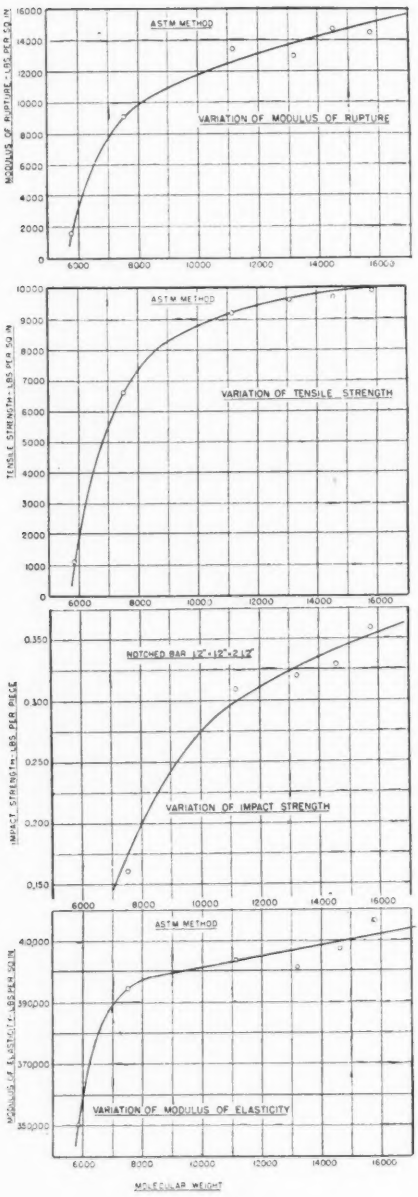


FIG. 3.

Variation of mechanical properties with molecular weight of mixed vinyl chloride and vinyl acetate resins.

strength rises to 4.25 tons/sq. in. and E (determined by bending) is about 0.84×10^6 lbs./sq. in. These are the values at room temperature; at liquid air temperature the strength and elasticity in the C stage rise to 4.95 tons/sq. in., and 2.13×10^6 lbs./sq. in. respectively.

It is possible in the case of vinyl resins, to connect the mechanical properties with the number of molecules in the micelles (28); the molecular weight of the polymer is determined from measurements of viscosity, and the use of Einstein's (29) equation. Fig. 3 (for which I am indebted to the Editor of the Industrial and Engineering Chemistry) gives such a comparison.

The isogel is held together by two kinds of bonds: (1) the primary chemical bonds holding the molecules together, (2) secondary bonds, also called "van der Waal's" forces. Primary bonds are the familiar links of organic chemistry; their magnitude can be computed from a knowledge of the heat of combustion associated with a particular linkage and of the variation of the energy of the link with the separation between the component atoms.

Secondary bonds are cohesive forces which can hold molecules together where there is no actual chemical combination; they can arise in various ways. For instance molecules or atoms which may be electrically neutral over a period of time will produce alternating electric fields having finite instantaneous values; these electric fields will induce charges on surrounding molecules and cohesion will result. Or again, some molecules, although electrically neutral as a whole, have a permanent dipole characteristic because their positive and negative charges are separated by a certain distance. It is possible to compute the magnitude of these van der Waal's forces, and as may be expected they are much smaller than those of the primary bonds.

J. H. de Boer (30) has calculated the strength and modulus of elasticity of phenol formaldehyde assuming that (1) the bonds are all primary (2) the bonds are all secondary. The results are given below.

TABLE I.

	Strength.	Modulus of Elasticity.
Primary Bonds only ...	4300 kg./sq. mm. (2720 tons/sq. in.)	11,000 kg./sq. mm. (6970 tons/sq. in.)
Secondary Bonds only...	39 kg./sq. mm. (25 tons/sq. in.)	45 kg./sq. mm.) (28 tons/sq. in.)
As determined by our experiments	12.0 kg./sq. mm. (7.6 tons/sq. in.)	544 kg./sq. mm. (345 tons/sq. in.)

If we compare the theoretical figures with those given by experiment, we see that the resin is much weaker than it should be, even assuming that there were no primary bonds. On the other hand, its modulus of elasticity is far greater than if secondary bonds alone were acting.

Now a discrepancy between the theoretical and experimental tensile strengths of materials is quite general and is not confined to resins and glasses. Similar discrepancies are found in metals and in crystals, and the beautiful work of A. A. Griffith (31) (chiefly with glass) suggests that the discrepancy, at least as far as brittle materials are concerned, is due to long thin submicroscopic cracks causing local concentrations of stress far above the mean value. It should be noted, however, that cellulose shows good agreement between theoretical and observed strengths (32) and elastic moduli (33), and that the stress concentration theory cannot be true for materials such as zinc, where to explain the weakness of a wire of 1 mm. diameter it would be necessary to assume the existence of a crack 1 cm. long (34).

With all diffidence I should like to ask whether the existence of initial strains in the isogel structure, as found by Filon and Harris (26), might not provide a supplementary, or possibly an alternative, explanation of the fact that resins and glasses may have a low strength yet a high elastic modulus. The weakness of

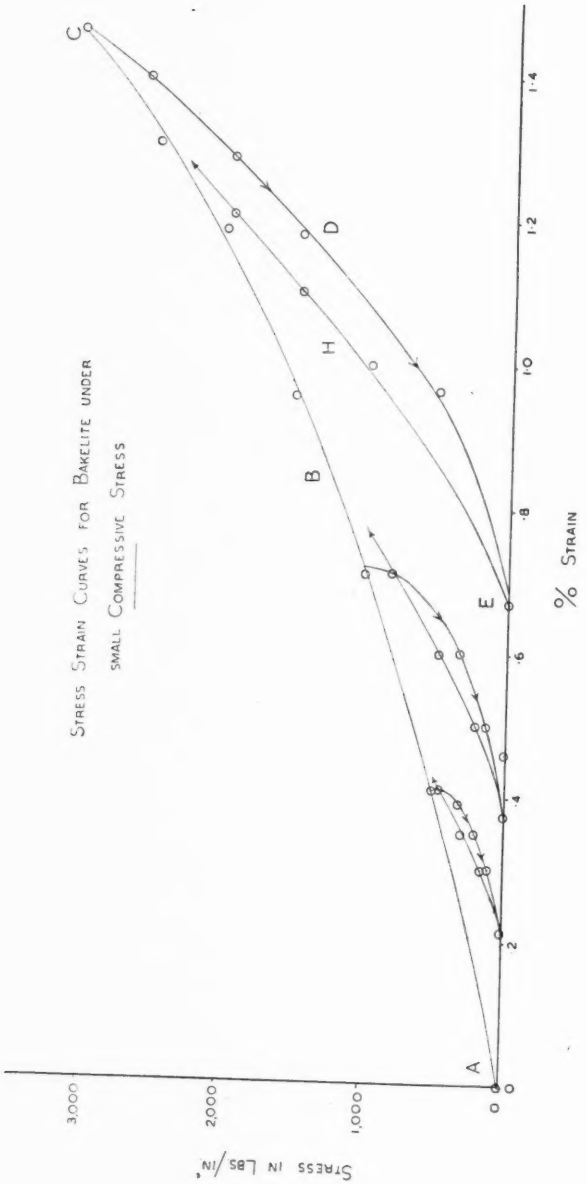


FIG. 4.
Hysteresis of cresol resin.

the material in tension might be explained by assuming (in accordance with the phenomenon of syneresis) that the solid portion of the isogel is in a state of contraction relative to the less condensed portions. Provided that these less condensed portions of the isogel remain under pressure up to the point of fracture the tensile strength of the resin as a whole will be correspondingly reduced. But by the principle of superposition the value of Young's Modulus will not be affected since both condensed and uncondensed portions suffer deformation under load. Thus while the strength will be much below the theoretical value the magnitude of the elastic modulus will lie between that for purely secondary and purely primary binding according to the degree of condensation.

BEHAVIOUR OF BAKELITE UNDER COMPRESSION.

1. *Small Compressive Stresses.*

Fig. 4 (curve ABC) shows that as we compress bakelite (cresol resin) its elastic modulus steadily rises. If, however, instead of continually increasing the applied load we unload and then reload again, the stress-strain curve describes a loop of which CDEH is a typical example. Experiment shows that the shape of a loop such as CDEH, is entirely unaffected by what may have been done previously in the way of loading and unloading, provided that the stress C at which unloading begins is higher than any previously applied stress. In mathematical language we can say that the shape of the characteristic CDEH is uniquely determined by the magnitude of C.

One is at first inclined to explain the existence of a permanent deformation such as AE, by supposing that plastic flow has taken place and to compare the effect with that shown by a metal when stressed above its yield point. But further consideration shows that such an analogy is false.

First of all, we find that if after the bakelite is given a permanent deformation AE it is heated for about an hour at 110° C. a recovery of quite considerable magnitude takes place, as shown in Fig. 5. On reloading the specimen the curve approximates to the original curve ABC and is quite unlike EHC. The deformation is not therefore of the nature of an irreversible permanent flow but is apparently due to a " freezing up " of the elastic restoring forces.

Secondly, the fact that the shape of the unloading and reloading curve is uniquely determined by the stress at which unloading begins, differentiates the phenomenon from that of plastic flow. In a ductile material stressed above its elastic limit, it is quite true that a different characteristic will be obtained on unloading and that there will be a permanent deformation at zero stress. But on reloading, instead of getting a loop like CDEH, the curve will retrace its shape back to the strain at which plastic flow took place. We can only get a loop if after unloading we reverse the stress so that the material is taken above its plastic point for tensile stress so that the specimen is thereby stretched back to its original length. But the size of this loop will depend not only on the stresses applied, but on the time during which plastic flow is allowed to take place.

The behaviour of bakelite is a true *hysteresis* effect, exactly of the same kind as the magnetic hysteresis of ferro-magnetic materials. Stone and cast iron behave in the same way and H. Schlechtweg (35) has described these materials as being " non-linear elastic " materials, since though they do not obey Hooke's Law even approximately the strain is uniquely determined by the stress, while in plastic materials the strain is also a function of the time. The hysteresis of bakelite, stone, and cast iron may similarly be described as " elastic hysteresis " in contrast to the " plastic hysteresis " of ductile materials.

2. *Large Compressive Stresses.*

Fig. 6 shows stress against strain up to about 16,000lbs. per sq. in. The experimental results are shown by the circles. The curve is derived from an

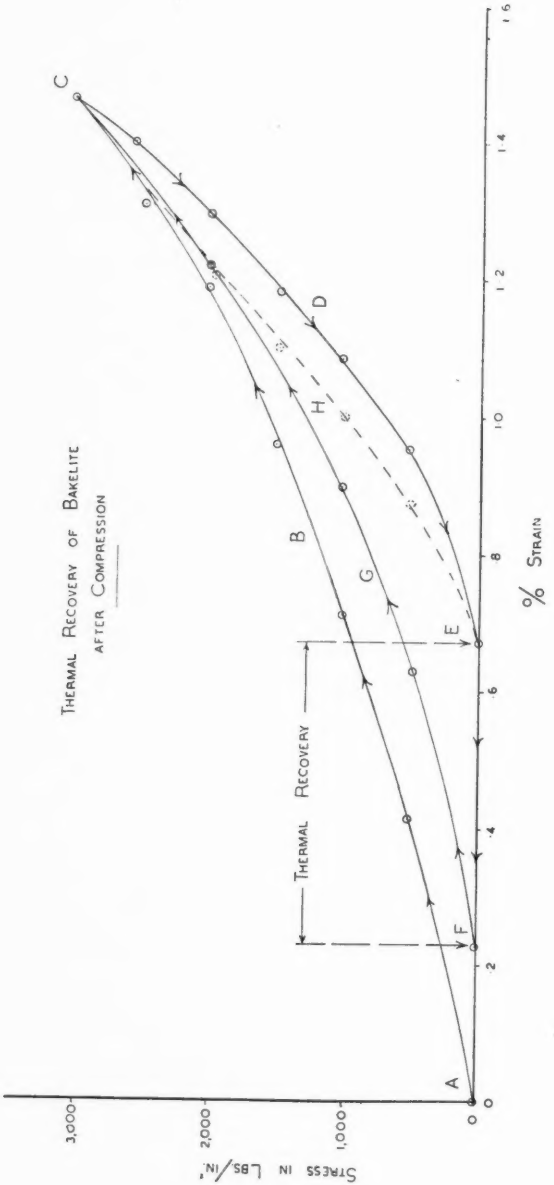

THERMAL RECOVERY OF BAKELITE
AFTER COMPRESSION
THERMAL RECOVERY
% STRAIN
STRESS IN LBS/IN²
A
B
C
D
E
F
G
H
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1,000
2,000
3,000

FIG 5.

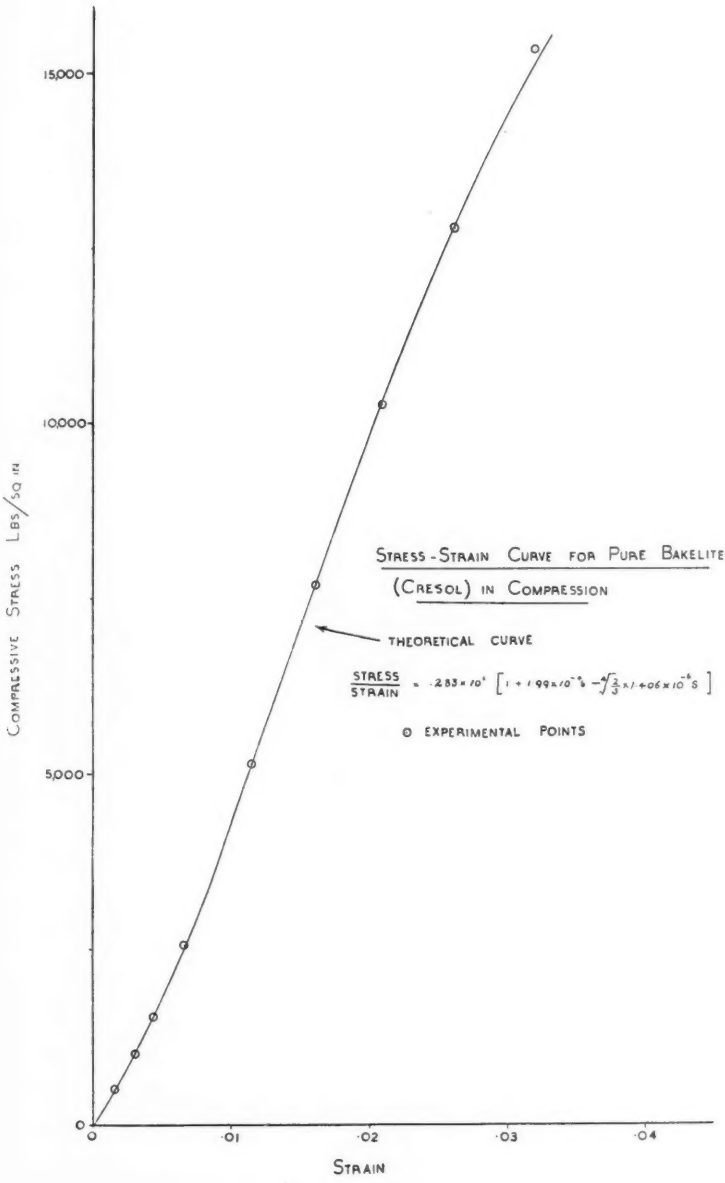

15,000
10,000
5,000
0
COMPRESSIVE STRESS LBS/SQ IN
0
·01
·02
·03
·04
STRAIN
STRESS-STRAIN CURVE FOR PURE BAKELITE
(CRESOL) IN COMPRESSION
THEORETICAL CURVE
STRESS/STRAIN = ·283×10⁵ [1 + 1·99×10⁻⁵S − √(⅔×1·06×10⁻⁵S)]
O EXPERIMENTAL POINTS

FIG. 6.

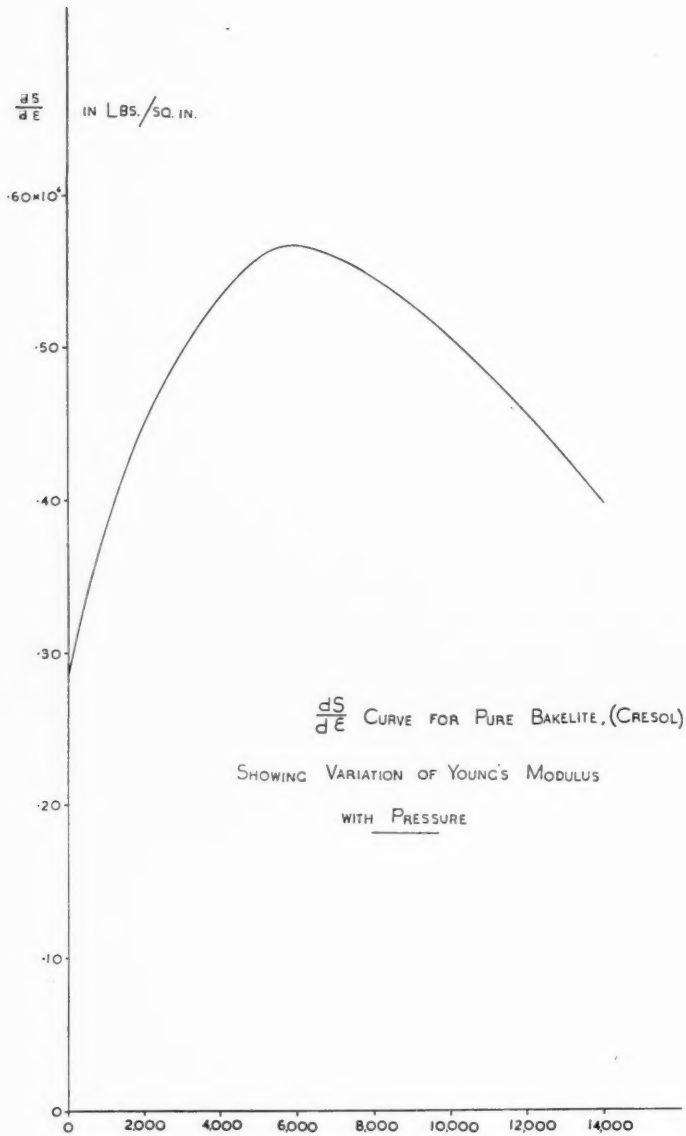


FIG. 7.

Variation of Young's Modulus of cresol resin under compression.

expression, due to H. Schlechtweg (35), obtained by a generalisation on dimensional principles of Grübler's (36) empirical equation, which has been fully confirmed by investigations of the elastic properties of stone and cast iron. Its general form is

$$s/\epsilon = E_0 \left[1 + \{ B - C\sqrt{(2/3)} \}\, s - L\,(2/3)^{\frac{1}{2}}\, s^{3/2} \right] \quad . \quad . \quad (1)$$

where s is the compressive stress.

ϵ is the strain.

E_0 is the value of Young's Modulus at zero stress.

B is a constant called the compressive sensitivity.

C is a constant called the shear sensitivity.

L is a constant called the combined shear compressive sensitivity.

For cresol resin $B - C\sqrt{(2/3)} = 1.99 \times 10^{-4}$ and $L = 1.406 \times 10^{-6}$ (inch-pound units). Since L is small in comparison with $B - C\sqrt{(2/3)}$ its effect only becomes appreciable when the stress is large. For small stresses the shape of the curve is therefore a hyperbola and the ratio of the stress to the strain is proportional to the stress.

By drawing tangents to the curve shown in Fig. 6 it will be seen that E at first increases to a maximum value and then decreases. The exact variation of E with stress (obtained by differentiating Schlechtweg's expression) is shown in Fig. 7.

FIG. 8.

Fragments of specimen of cresol which was originally cylindrical.

Up to about 6,000lbs. per sq. in. the value of E steadily increases so that the elastic modulus of bakelite for small stresses could be improved by giving it in some way or another a permanent compression of magnitude somewhat less than this amount.

It should be noted that all the above figures refer to cresol resin. Phenol resins have better characteristics and the experimental results given in Table I refer to such resins.

3. *Compressive Failure.*

Shortly before failure takes place the stress-strain curve departs from the Schlechtweg expression. The failure is of a sudden explosive kind and the specimen splits up into a number of columns or needles whose major axes are

parallel to the direction of the applied load (see Fig. 8). Results of tests on cresol resin cylinders 1in. high by ½in. diameter gave ultimate strengths of 24,350lbs. per sq. in. and 21,000lbs. per sq. in.

BEHAVIOUR OF BAKELITE UNDER TENSION.

Cresol resin is weak in tension and breaks at about 5,000lbs. per sq. in. The value of Young's Modulus continually decreases with increase in tension and the nature of the variation can again be expressed by Schlechtweg's equation modified to take into account the opposite sign of the applied stress. It then becomes

$$s/\epsilon = E_0 \left[1 - \{ B + C\sqrt{(2/3)} \}\, s + Ls^{3/2}(2/3)^{\frac{1}{2}} \right] \quad . \quad . \quad (2)$$

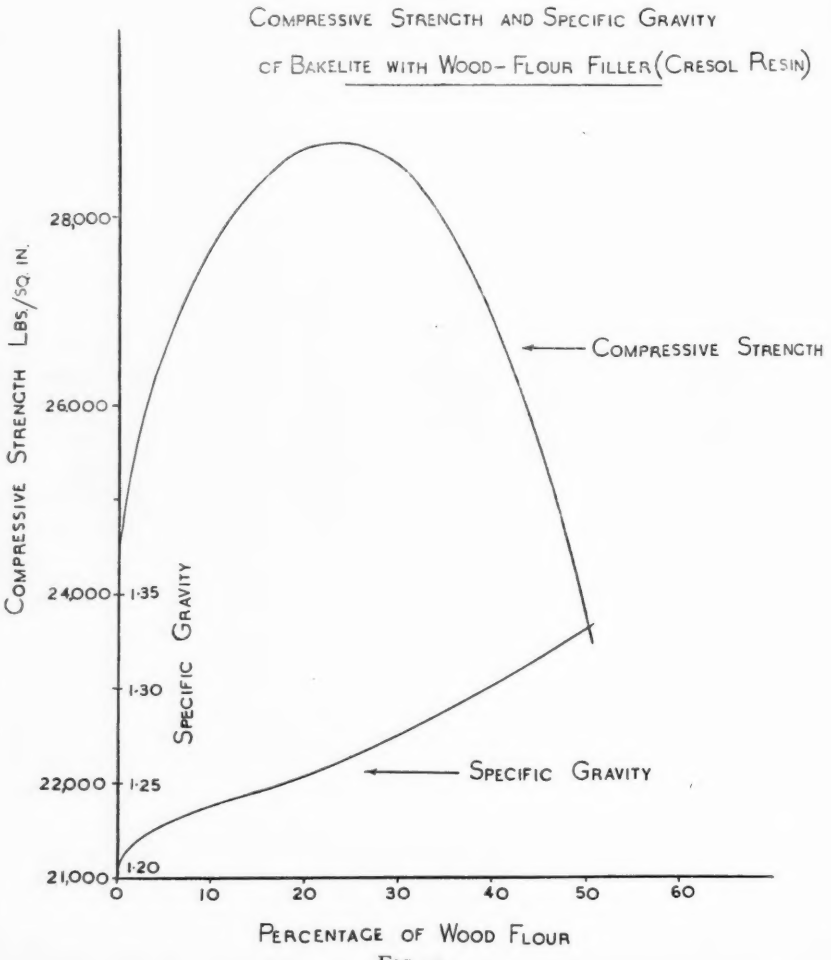


FIG. 9.

Effect of wood flour on compressive strength and specific gravity of cresol resin.

The nature of failure is characteristic of a brittle material; there is no flow and any concentration of stress causes premature breakdown. The tensile strength of stone is so small that the term in L in equation (2) can be neglected, but this is not the case with bakelite even with cresol resin.

Discussion of Behaviour of Bakelite.

The most striking property of pure bakelite is the variation of Young's Modulus with the sign and magnitude of the applied stress. Prandtl (2) has pointed out that such a variation can be simulated by a structure composed of a pile of interlocked beams (like a carriage spring). Increase of pressure will tend to flatten them out and cause an increase in Young's Modulus up to a maximum when they are quite flat, after which it will decrease again as the beams are bent in the opposite direction. Tension, on the other hand, will cause a continuous increase in curvature and a continuous decrease in Young's Modulus.

The nature of the fracture, both in tension and compression, suggests that the existence of a maximum principal stress is the cause of failure. The investigations of M. M. Frocht (37) are in agreement with this view.

We shall see that the type of failure is profoundly modified by the addition of powdered fillers or of continuous reinforcement and that shear failure then becomes the usual type.

Properties of Bakelite with Filler.

Phenol formaldehyde is not usually used without a "filler" and wood flour is commonly used for this purpose. The effect of such a filler is to increase the compressive strength with some increase in density. Fig. 9 shows the effect of variation in the proportion of wood flour to resin on the compressive strength and density. We have not yet had time to study the corresponding variation in the constants B, C, and L of Schlechtweg's expression, but we have observed that the type of fracture changes at about 10 per cent. of wood flour. Below this percentage the break is of an explosive kind; above this percentage failure takes place by shearing along a plane at approximately 45° to the direction of compressive failure, after a good deal of plastic deformation.

The properties of the resin can thus be considerably improved by the addition of a filler. Very similar results are obtained when carbon black is added to rubber (38). It is clear that there is scope here for a considerable amount of research.

Tension Reinforcement.

Although the use of a powdered filler improves the mechanical properties of bakelite resin, greater strength in tension can be obtained by the use of a continuous reinforcement, and it is then possible to obtain a material having comparable compressive and tensile strengths. Table II below (taken chiefly from Ref. 39) shows the tensile strengths of a number of common substances.

Table II.

Material.	Tensile Strength. Tons/sq. in.	Density.	Max. Strength/Density.
Egyptian cotton (dry) ...	18-23	1.55	14.8
Indian cotton (dry) ...	18.5-23.5	1.55	15.1
American cotton (dry) ...	Up to 28	1.55	18.0
Bamboo	24	—	—
Flax	23-70	—	—
Jute	24	—	—
Hemp	58.2	—	—
Ramie	49.1	—	—
Apocynum sibiricium ...	73.4	—	—

TABLE II (*continued*).

Material.	Tensile Strength. Tons/sq. in.	Density.	Max. Strength/Density.
Agave Americana ...	24.8	—	—
Cocos mucifera	18.3	—	—
Raw silk	28.4	—	—
Merino wool (scoured) ...	10.6	—	—
Camel hair	11.7	—	—
Chitin	37	—	—
Steel	Up to 100	7.85	12.7
Spruce	5	0.5	10
Aluminium	9	2.6	3.5

It will be seen that cotton appears to be one of the most suitable of the common materials. It is easily obtainable woven into fabric and can easily be impregnated; the elastic modulus of the thread is comparable with that of bakelite so that when the composite material is strained the adhesion forces between the bakelite and the reinforcement do not reach high values. The use of a textile reinforcement is advantageous because of the endurance of such materials to repeated bending; this is illustrated by some results obtained by A. Schopper (40) and reproduced in Table III below.

TABLE III.

Material.	No. of bendings required to cause fracture.
Wool	100,000,000
Cotton fabric	3,170,000
Artificial silk	631,000
Paper	320,000
Jute fabric	10,000
Aluminium foil	32

The figures in Table II refer to fibres. To obtain a thread these fibres have to be twisted together and the resulting mechanical system is a complicated one (41). The central fibres remain untwisted and the surface fibres get the greatest amount of twist. A tensile load applied to the thread is taken chiefly by the core as the outermost fibres have a considerable inclination to the direction of the applied load. With a proper amount of twist, failure eventually takes place by breakage of the core fibres, because the friction produced by the twist in the outer fibres is sufficient to prevent slipping in the core. The core can be defined as the central portion of the thread bounded by a surface in which the force of friction is just equal to the true breaking strength of the fibres. Fig. 10 shows that the strength of the thread never exceeds about 75 per cent. of the strength possible if all the fibres were parallel and prevented from slipping by some agency other than twist; it will also be observed that practically the whole strength of the thread is due to the core. Fig. 10 refers to unimpregnated thread which has not yet been woven into fabric.

It will be seen that a solid rod of cellulose such as can be produced by the coagulation of viscose should be more suitable for our purpose than a thread of twisted fibres. Unfortunately, preliminary experiments show that such coagulated material (familiarly known as rayon) is not wetted by phenol formaldehyde. The strength of rayon is also much reduced by moisture (42) (see Table IV below), though this might not be important if the material were well protected by impregnation. Experiments are being continued, however, to see if these difficulties cannot be overcome.

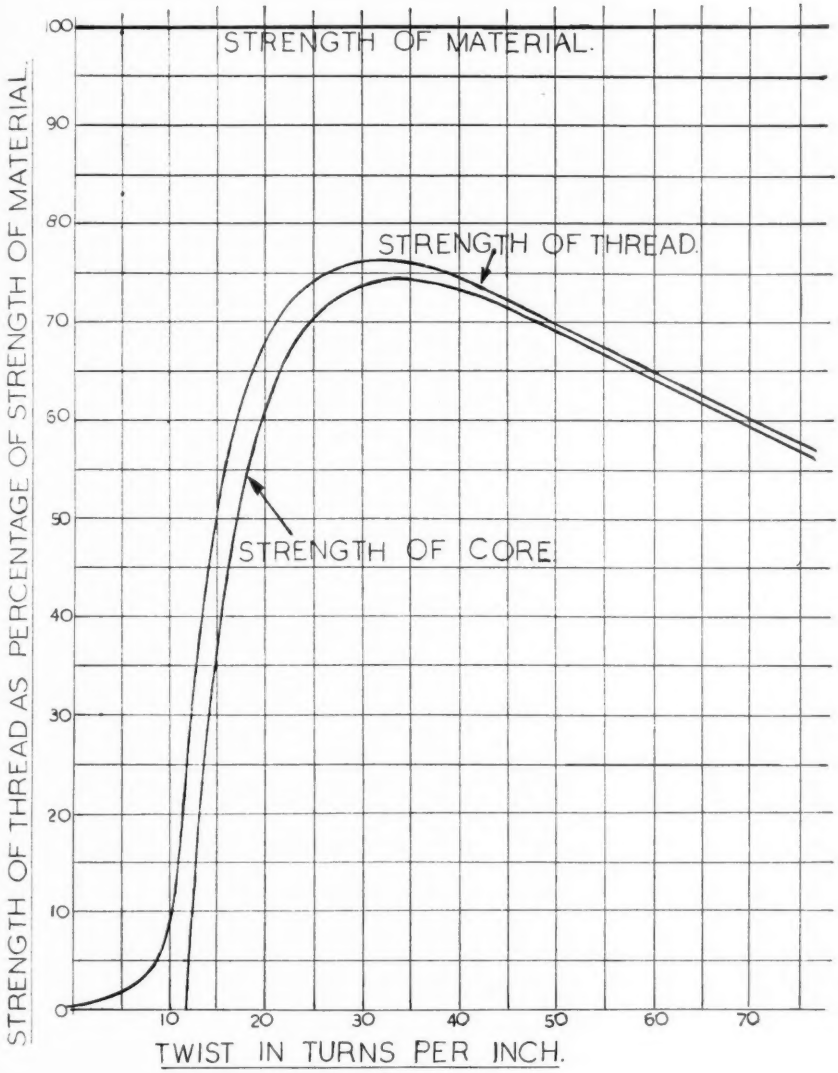


FIG. 10.

Effect of twist on strength of thread.

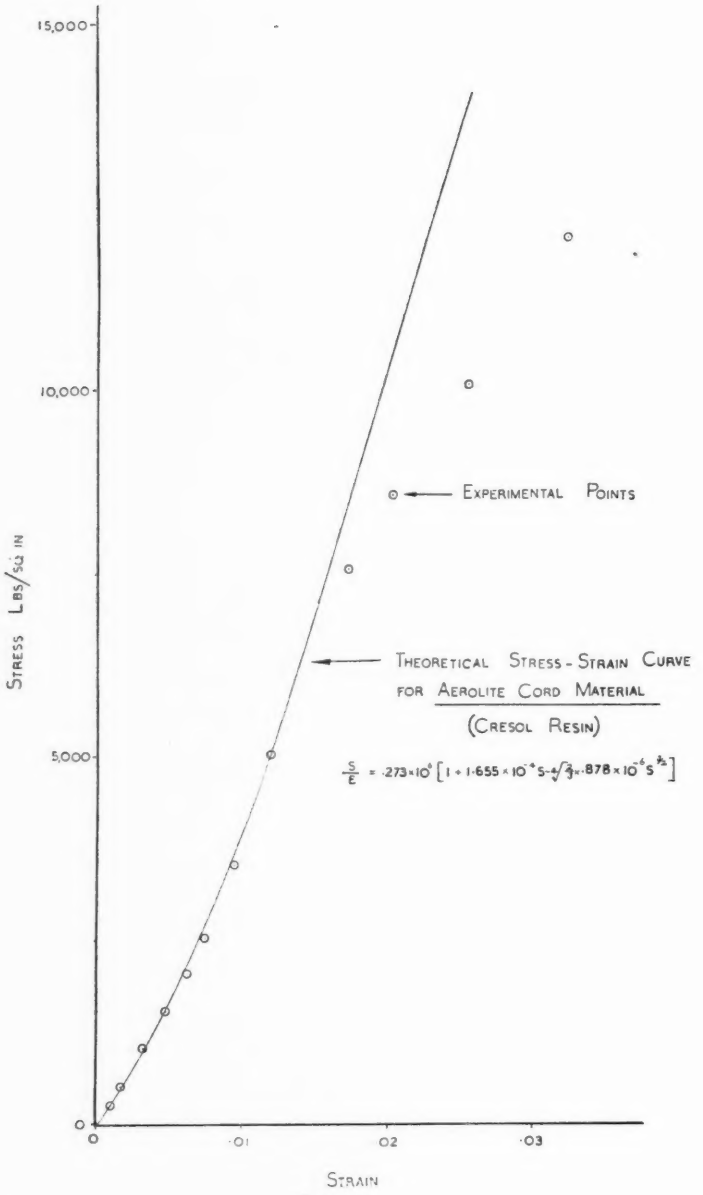


FIG. 11.

Stress-strain characteristics of aerolite cord material under compression.

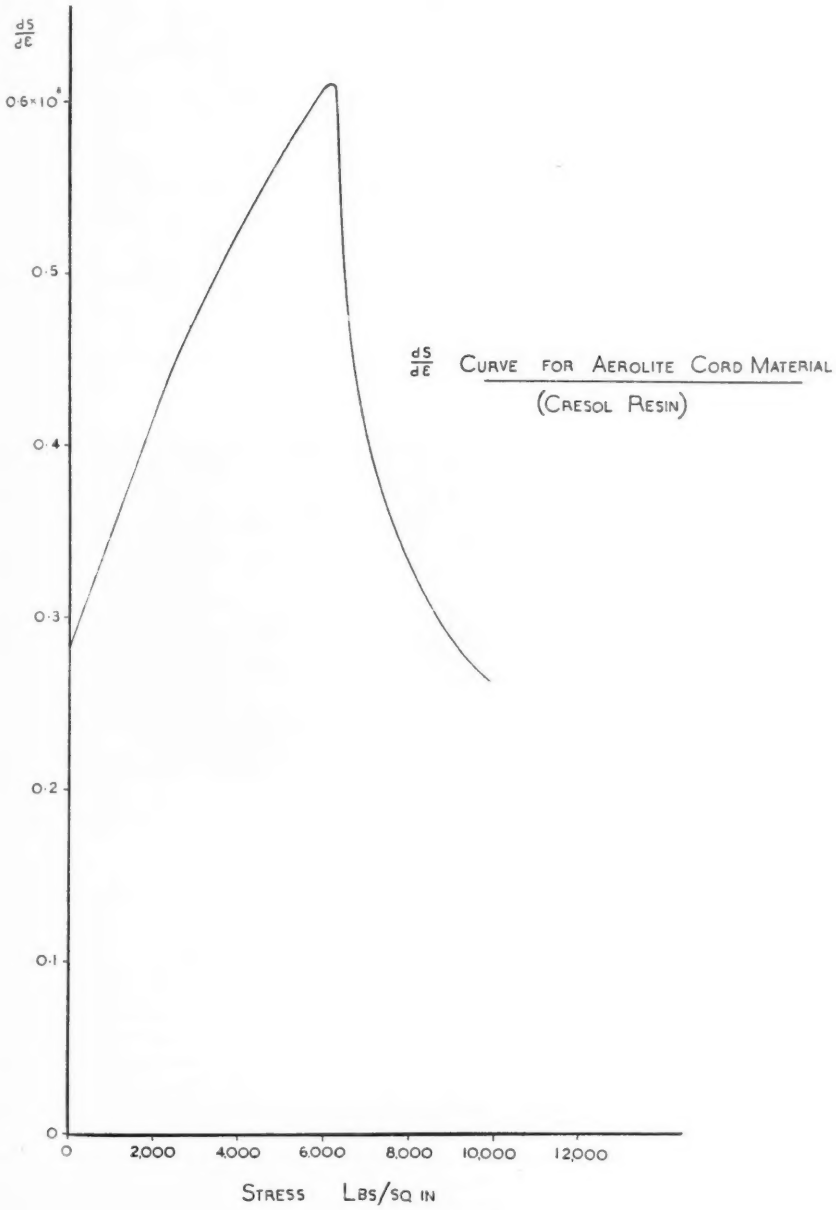


FIG. 12.

Variation of Young's Modulus of aerolite cord material under compression.

TABLE IV.

VARIATION OF STRENGTH WITH MOISTURE CONTENT.

Material.	Ultimate Strength in tons/sq. in. at humidity of 0%	50%	70%	100%
Ramie	18.0	25.3	24.6	5.9
Cotton	18.4	26.1	24.0	49.6
Camel hair ...	11.8	10.3	10.7	10.3
Wool	9.2	9.3	12.1	4.2
Silk	22.6	26.9	24.0	33.0
Artificial silk ...	9.9	5.2	6.0	3.1

PROPERTIES OF CORD AEROLITE IN COMPRESSION.

To distinguish bakelite reinforced with a continuous tension reinforcement from other kinds, I propose to call such a material "Aerolite." I am aware that this practice is not free from objections since the word is a registered trade mark and flatters my own firm (which is not, of course, the originator of such materials), yet we have found it necessary in our work to have some distinctive name for such products.

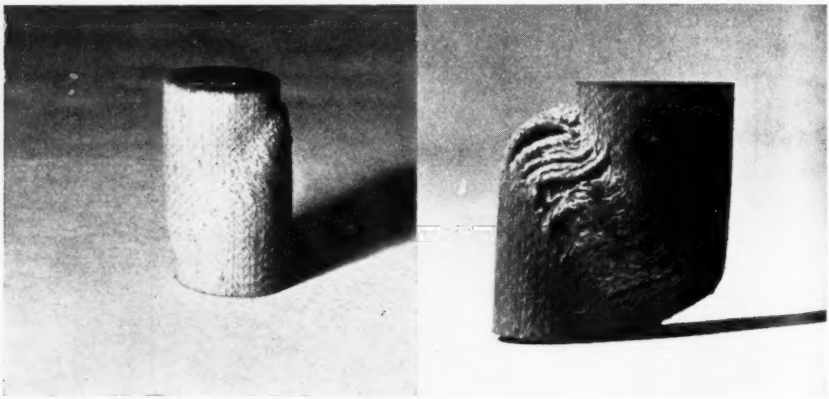


FIG. 13.

Failure under compression of aerolite cord material (cresol resin impregnation), cf. Fig. 8.

Now as Caldwell and Clay (43) pointed out in 1924 in their pioneer work on synthetic resin airscrews, by having a material in which 90 per cent. of the reinforcement is in the warp, an extremely strong product in tension along the warp is obtained. Such material we will designate as Cord Aerolite; its production in this country is due to Mr. C. D. Philippe, of Messrs. Bakelite, Ltd. Cord aerolite gives the strongest reinforcement whenever the applied tensile loads are limited to directions parallel to the cords. It represents the simplest possible type of reinforcement.

This kind of reinforcement has very little effect on the ultimate compressive strength, which remains about the same as for the pure resin. Fig. 11 shows, however, that the presence of the cord profoundly alters the stress strain characteristic above 6,000lbs. per sq. in. and the nature of the ultimate failure as is shown in Fig. 13.

Up to about 6,000lbs. per sq. in. Schlechtweg's equation is obeyed and the constants are not very different from those of pure cresol resin. Above this

stress, however, the strain increases rapidly for a given stress and something similar to plastic deformation takes place; the ds/de curve (see Fig. 12) shows a very rapid falling off in the value of Young's Modulus. We see, therefore, that apart from eliminating the brittleness (*i.e.*, the liability for failure to take place under the greatest principal stress instead of the greatest shear) no increase in the ultimate strength or in the value of Young's Modulus is obtained by the use of cord reinforcement.

If we regard the cords as a series of columns stabilised in compression by the surrounding resin (see Fig. 18), then it appears that the resin ceases to have a stabilising influence at about 6,600lbs. per sq. in. Assuming a value of Poisson's ratio of one-third, this corresponds to a lateral stress of about 2,200lbs. per sq. in. This is the value of the moulding pressure under which the material was made. Experiments are now in progress to test whether such a relationship between moulding pressure and plastic flow holds good in general.

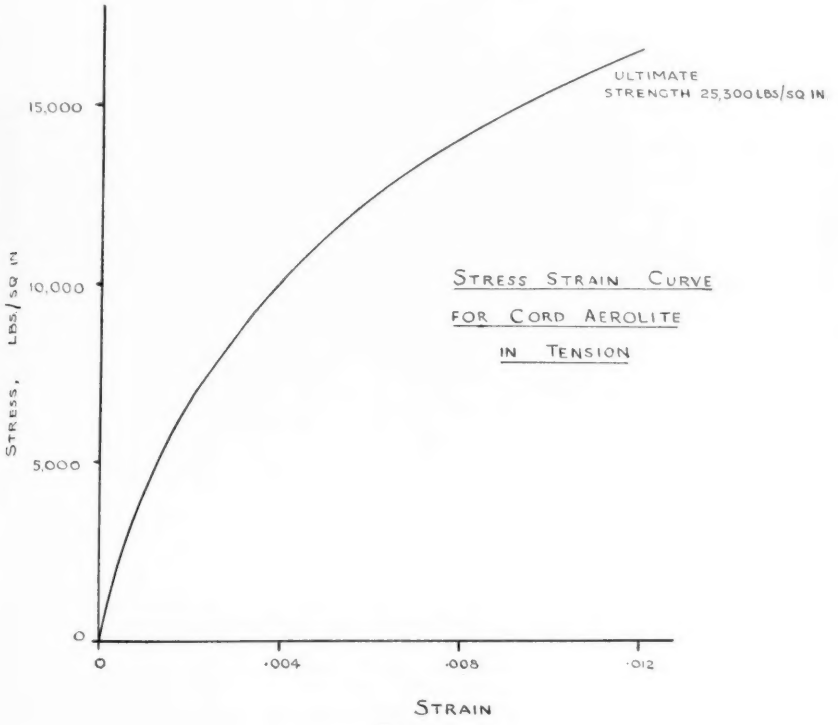


FIG. 14.

PROPERTIES OF AEROLITE IN TENSION.

The cord reinforcement has a remarkable effect on the properties in tension. It increases the tensile strength to about 26,000lbs. per sq. in. and Young's Modulus to at least 2.0×10^6lbs. per sq. in. (up to 0.2 per cent. strain). Fig. 14 shows a stress-strain curve for material moulded at one ton per sq. in. Up to 6,000lbs. per sq. in. hysteresis, but no " elastic after effect " is present; above this stress the strain rises gradually on applying the load and does not reach a final steady value until a few minutes after the time of application. Again,

therefore, as in compressive behaviour, it appears as if the resin and cord reinforcement are able to act together so long as the lateral stress is less than the moulding pressure. Above this stress the cord reinforcement shrinks away from the surrounding resin which then falls out of action. This view is in agreement with the fact that the ultimate strength of the material is equal to that of the reinforcement alone. This was verified by determining the strength of the cord material only (before impregnation) and then counting under a microscope the number of cords in the cross section of a tensile test specimen. The strength of the specimen was 1,150lbs., while that of the threads alone was 1,245lbs. (118 threads at 10.55lbs. for the strength of each thread).

EFFECT OF INITIAL COMPRESSION ON STRESSES IN BENDING

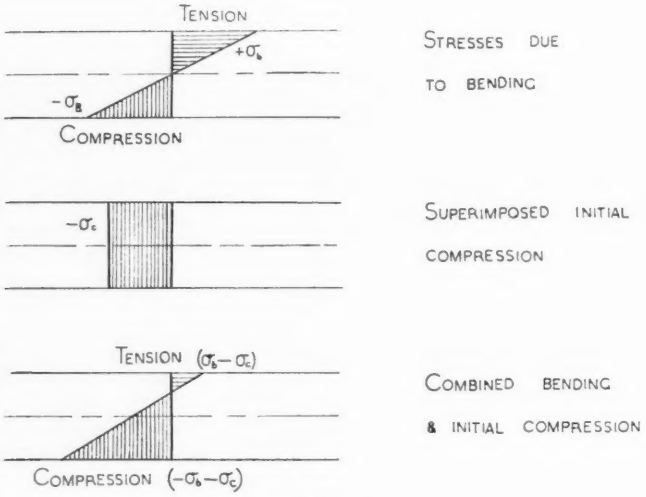


FIG. 15.

Not only is the ultimate strength dependent only on the reinforcement, but the value of Young's Modulus even at small stresses is chiefly determined by it. Thus, if we take fabric having twice as many threads in the warp as in the weft we shall find that the value of Young's Modulus, as well as the ultimate tensile strength, are approximately in the ratio of 2 : 1. We have verified this not only for cresol resin impregnation, but also for urea formaldehyde and methyl methacrylate resins.

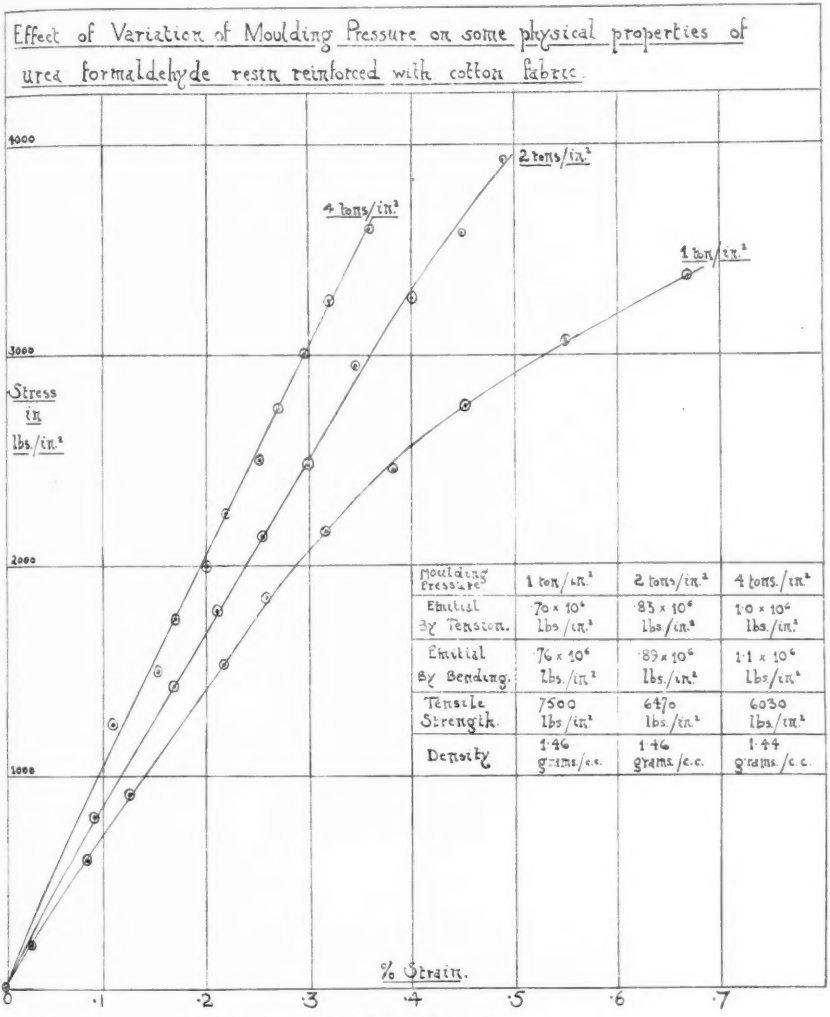
The process of moulding is one which we should expect would leave the resin in a state of compression relative to the fabric, because when the resin softens in the press it will experience a uniform hydrostatic pressure equal to the moulding pressure and the fabric will be correspondingly extended. When the resin hardens it will keep the fabric in this state of tension.

A number of other facts are explicable on such a view. Briefly they are as follow :—

1. Moulding at a low pressure gives a brittle material having properties like unfilled bakelite. A state of high initial compression, on the other hand, would

(exactly as in " Securit " glass) prevent fracture at surface cracks by displacing the neutral axis towards the tension side of the beam as shown in Fig. 15.

2. When fabric instead of cord material is used the stress at which elastic after effect becomes appreciable is numerically equal to the moulding pressure. Here, the bakelite, instead of being in continuous lengths parallel to the warp



Moulding Pressure	1 ton/in.²	2 tons/in.²	4 tons/in.²
Elastic By Tension.	7·0 × 10⁶ lbs/in.²	8·3 × 10⁶ lbs/in.²	10 × 10⁶ lbs./in.²
Elastic By Bending.	7·6 × 10⁶ lbs./in.²	8·9 × 10⁶ lbs./in.²	11 × 10⁶ lbs/in.²
Tensile Strength.	7500 lbs/in.²	6470 lbs./in.²	6030 lbs./in.²
Density	1·46 grams/c.c.	1·46 grams/c.c.	1·44 grams/c.c.

FIG. 16.

(as in the cord material), is broken up into a series of beads by the weft. These beads will clearly be pulled apart at such a strain as corresponds to the initial compression.

3. The value of Young's Modulus at low stresses increases somewhat with increase in moulding pressure. This is what we should expect from Schlechtweg's

equation if the resin is in a state of initial compression determined by the moulding pressure.

Fig. 16 shows results obtained with urea formaldehyde resin. Similar results have been obtained with bakelite and with methyl methacrylate (" Perspex ").

A mechanical model illustrating the effect of variation of moulding pressure on the properties of the reinforced resin is shown in Fig. 17. Here the cylindrical blocks represent the beads of resin in the fabric and the springs represent the warp. By inserting additional cylindrical blocks the initial tension in the springs is increased, and correspondingly the load (measured by the weights on the hook), which must be applied to cause the blocks to fall out, must be increased. It will also be found that at this load the ratio of load to extension undergoes a sudden reduction because when the blocks fall out of action all the load is taken by the springs.

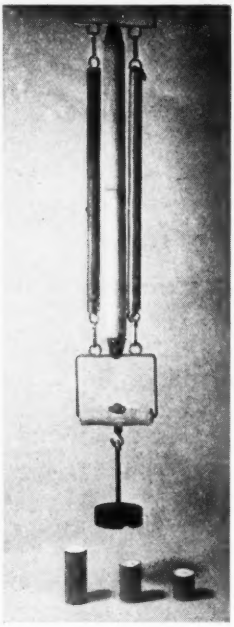


FIG. 17.

The springs representing the cord reinforcement are given an initial tension by the wood blocks. At an applied load equal to the initial tension the wood blocks fall out of the model.

MICROPHOTOGRAPHS.

Microphotographs of sections of cord aerolite under normal and polarised transmitted light are shown in Figs. 18 and 19. In Fig. 18 the dark objects are cross sections of the cords which are seen to consist of three groups of three threads. These cords are surrounded by the transparent resin which fills up all the interstices and forms columns parallel to the cords.

Fig. 19 was obtained with a crossed analyser and polariser using "Polaroid" discs, whose great diameter in comparison with that of Nicol prisms makes them advantageous for this work. In the absence of double refraction no light would reach the camera; cotton is always doubly refracting, whether strained or not, but bakelite only becomes doubly refracting under strain. In Fig. 19 the doubly refracting cotton appears grey and the resin is dark in comparison. But round each cord there is a line of bright light suggesting a high adhesion stress in the resin such as might be produced if resin and cord were in a state of initial stress relative to one another.

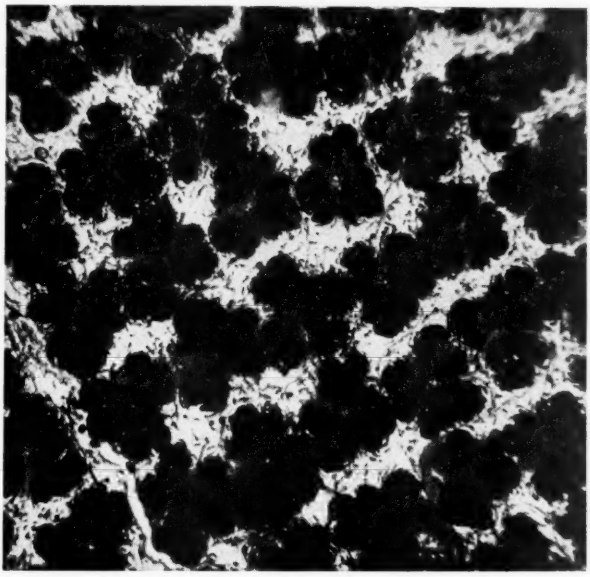


FIG. 18.

Microphotograph by transmitted light of section of aerolite cord material. Each cord has nine threads and is seen to be embedded in the resin which forms continuous columns parallel to the cords.

AEROLITE AND BAKELITE BEAMS.

Since the value of Young's Modulus depends both on the magnitude and sign of the stress, the ordinary relation (generally written $p/y = M/I = E/R$) between the deflection, the stress, and the applied bending moment does not apply.

Provided that we know the relation between stress and strain it is possible, however, to compute by graphical means the magnitude of the deflection for a given bending moment. Conversely, by measuring the extreme stresses on the beam and knowing the applied bending moment we can deduce the relation between stress and strain in compression and tension.

This method of solution is due to C. Bach (44), and takes a particularly simple form for rectangular beams (45) as follows:—

$$M = \{ h^2 b/(\epsilon_1 + \epsilon_2)^2 \} \int_{-\epsilon_1}^{\epsilon_2} f(\epsilon)\, \epsilon d\epsilon \quad . \quad . \quad . \quad . \quad (3)$$

where M = applied bending moment;
h = height of beam;
b = breadth of beam;
and ϵ_1 and ϵ_2 are the extreme tensile and compressive strains.
The integral is determined by graphical means.

H. Deutler (46) has solved equation (3) analytically for the particular case of a material obeying the Schlechtweg relation, but so weak in tension that the term L can be neglected. This is not the case with bakelite where the tensile strength is sufficiently great for the L term to have a considerable effect even in tension.

The position of the neutral axis, in beams where Hooke's Law is inapplicable, will vary with the magnitude of the applied bending moment or, what is equivalent, with the deflection. The hysteresis of the material will also, therefore, as

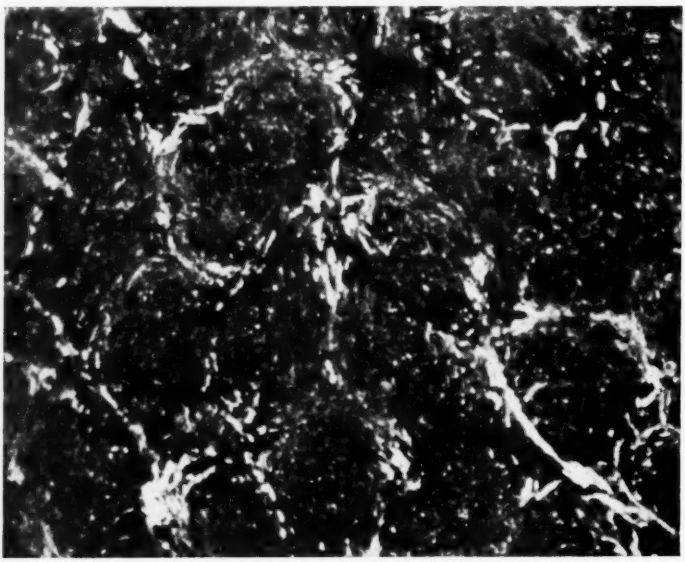


FIG. 19.

Microphotograph of cord aerolite between crossed "Polaroid" discs. A stress pattern surrounds the cords.

Deutler has pointed out, affect the position of the neutral axis even in a test where a continually increasing bending moment is applied. Thus in a beam made of a material like bakelite, where the neutral axis continually moves towards the compressive side, the existence of hysteresis must affect the place where the stress changes from compressive to tensile stress. The effect of hysteresis is, however, not capable of any straightforward analytical treatment and will probably always have to be neglected.

We have not yet had an opportunity to investigate the behaviour of bakelite beams, but from the above it will be clear that the "modulus of rupture" is not a quantity of any fundamental significance and the fact that its magnitude depends so markedly on the shape of the beam and that it is always greater than the real tensile strength is easily understood.

EFFECT OF NOTCHES ON TENSILE STRENGTH.

A noteworthy illustration of the fundamental modification that takes place in the properties of bakelite when reinforced is given by the behaviour of notched tension specimens made of aerolite. These notches cause an apparent increase in the tensile strength—a phenomenon characteristic of ductile materials and apparently first noticed by Kirkaldy (47) in 1862. Fig. 20 shows the results of tests on aerolite material having 26 threads per inch in warp and weft (and therefore rather low ultimate tensile strength). It will be seen that the apparent tensile strength rises from 9,380lbs. per sq. in. to 13,100lbs. per sq. in. as the depth of the notch is increased.

This behaviour characteristic of ductile materials is generally explained as due to the resistance to deformation in the notched portion caused by the adjacent unnotched material.

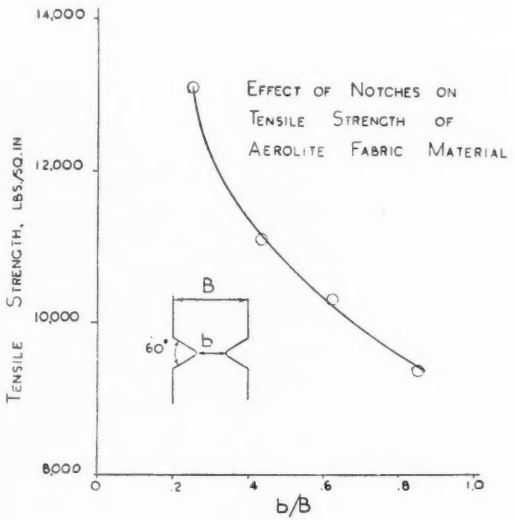


FIG. 20.

Similar tests with pure cresol resin gave widely scattered results and failure generally took place in regions remote from the notch.

GENERAL ELASTIC PROPERTIES OF AEROLITE.

Aerolite is an æolotropic material. When reinforced with ordinary fabric its axes of symmetry correspond to the orthorhombic system of crystal symmetry and nine elastic constants are necessary to describe a general state of stress. Aerolite cord material corresponds to the tetragonal system (one axis of symmetry being parallel to the cords, with two other axes, both of the same length, at right angles to each other and the first axis). Six elastic constants are necessary to describe a general state of stress in such a system. These considerations are of importance because errors may arise in the determination of the elastic constants of the materials if formulæ derived for isotropic materials are applied without modification (48).

The determination of G (the modulus of rigidity) may in particular give rise to errors if carried out in the usual way by twisting a rod of the material. Only in the case of cord aerolite when the axis of the rod is parallel to the cords does such an experiment give a true result.

TABLE V.

SOME MECHANICAL PROPERTIES OF AEROLITE.

	Cord Material Cresol Resin (33 cords/inch).	Fine Fabric Material (80 threads/inch).
Tensile strength ...	25,000lbs./sq. in. along cords.	18,000lbs./sq. in.
Compressive strength ...	27,000lbs./sq. in. perpendicular to cords.	26,000lbs./sq. in.
Shear strength	5,800lbs./sq. in. parallel to cords.	9,000lbs./sq. in. perpendicular to fabric layers.
Young's Modulus ...	2.0×10^6lbs./sq. in.	1.1×10^6lbs./sq. in.
Modulus of rigidity ...	0.3×10^6lbs./sq. in.	
Impact (on standard specimen as used for spruce)	35ft. lbs.	8.7ft. lbs.
Density	1.34.	1.34.

THE ENERGY ABSORBING PROPERTIES OF AEROLITE.

The energy absorption of metals was studied by Lord Kelvin (49) many years ago and he showed that the law of damping could not be one in which the damping force is proportional to the velocity. It is only in recent years, however, that the damping properties of materials have attracted interest; the Izod, Charpy, and similar impact tests give some kind of information about the energy required to fracture a material, but none about the energy absorbed under working conditions—a quantity which must in general be of greater significance. The energy absorption of a material may be said to have the same kind of meaning in estimating its value for conditions of alternating stress as the elongation in estimating quality under static loading. Probably it is the difficulty of measuring such a small quantity that has led to its neglect.

When a material is strained, energy is used up partly in overcoming elastic forces and partly in doing work against the internal friction forces; the strain energy due to the elastic stresses is reversible, but the energy absorbed by the internal friction is dissipated as heat. The ratio of the energy absorbed to the elastic or strain energy is called the energy absorption of the material. This ratio becomes large if the material is stressed beyond the yield point, but it still has a finite value for indefinitely small displacements.

The energy absorption of a material is most easily determined from observations of the decay of torsional oscillations in a strip of the material. We found (50) that the magnitude of energy absorption in aerolite is higher than that in wood or metal. This, of course, is in accordance with the marked hysteresis effects shown under static loading, because each torsional oscillation corresponds to a hysteresis loop. Some values, which must be regarded as giving the order of magnitude only and not as accurate determinations (since energy absorption is in general a function also of temperature) are given below.

TABLE VI.

ENERGY ABSORPTION IN TORSIONAL OSCILLATION.

Material.	Percentage Energy Absorption.
Aerolite with fine fabric reinforcement (50) ...	24
Cord aerolite (50)	20
Bakelite with paper reinforcement (50)	18
"Novotext" (51)	12.5
Mahogany and walnut (50)	12
Zinc (52)	11.7
Aluminium (52)	1.1
0.9 per cent. carbon steel (52)	0.17
Nickel (52)	0.021

The energy absorption at small displacements is independent of the length or cross section of the specimen and of the amplitude or period of oscillation. It is a characteristic only of the material.

Energy absorption is not connected with fatigue, creep, or with flow in the material though, of course, if the amplitude of oscillation is sufficiently large to produce plastic deformation the absorption is much increased. The absorption continues indefinitely and after many millions of oscillations shows no signs of diminution. Single crystals appear to have no energy absorption (53) so that we conclude that the effect is connected with the existence of grain boundaries, and for pure metals the logarithm of the energy absorption at constant temperatures appears to be a linear function of the appropriate Debye temperature, suggesting that the process is due to scattering of the phonons of elastic energy by atoms at the Debye frequency.

The fact that the energy absorption is unaffected by practically every variable except the nature and state of the material means that we cannot represent the motion of a system with this type of damping by an equation of the form

$$m\ddot{x} + k'\dot{x} + cx = P \sin \omega t \quad . \quad . \quad . \quad . \quad (4)$$

A modification of this equation capable of mathematical development and in better agreement with the facts is that suggested by von Schlippe (54) as follows:—

$$m\ddot{x} + k/\omega\dot{x} + cx = P \sin \omega t \quad . \quad . \quad . \quad . \quad (5)$$

Equation (5) can be written in vector notation as

$$(c - \omega^2 m)\, X + jkX = P \quad . \quad . \quad . \quad . \quad (6)$$

which gives the amplitude of displacement as

$$A = P/\sqrt{\{(c - \omega^2 m)^2 + k^2\}} \quad . \quad . \quad . \quad . \quad (7)$$

whereas equation (4) gives the expression

$$A' = P/\sqrt{\{(c - \omega^2 m)^2 + k'^2\omega^2\}} \quad . \quad . \quad . \quad . \quad (8)$$

The maximum amplitude A_R is obtained when $c = \omega^2 m$. This corresponds to resonance between the externally applied vibration and the natural frequency of the system.

$$A_R = P/k \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If V is the dynamic magnifier, *i.e.*, the ratio of the displacement at resonance to the displacement under an equal static load, then

$$V = A_R/A_{stat} = A_R/(P/c) = c/k \quad . \quad . \quad . \quad . \quad (10)$$

It will be seen that the value of the dynamic magnifier is not affected by the frequency of the vibration at resonance as is the case for a system governed by equation (4).

Fig. 21 shows the variation of amplitude with applied frequency when $k = 0.153\ c$ (corresponding to aerolite) and $k = 0.00108\ c$ (corresponding to steel). The curves give an idea of the relative behaviour of bars made of aerolite and steel having the same natural frequencies. The dynamic magnifier for steel is thus about one hundred and forty times greater than that of aerolite.

Fig. 21 illustrates a characteristic of aerolite of importance in aircraft construction. No one who has flown a metal Moth after a wooden one can fail to have noticed the increase in the amount of engine vibration which reaches the cockpit of the metal machine. Yet, apart from the fact that in one the engine mounting and fuselage are of wood while in the other they are of steel, the machines are identical. The use of aerolite should result in additional freedom from vibration. Measurements of the energy absorption of metal and wooden wings carried out by the D.V.L. (55) confirm this difference. Of course, in such composite structures energy absorption will also be caused by friction between

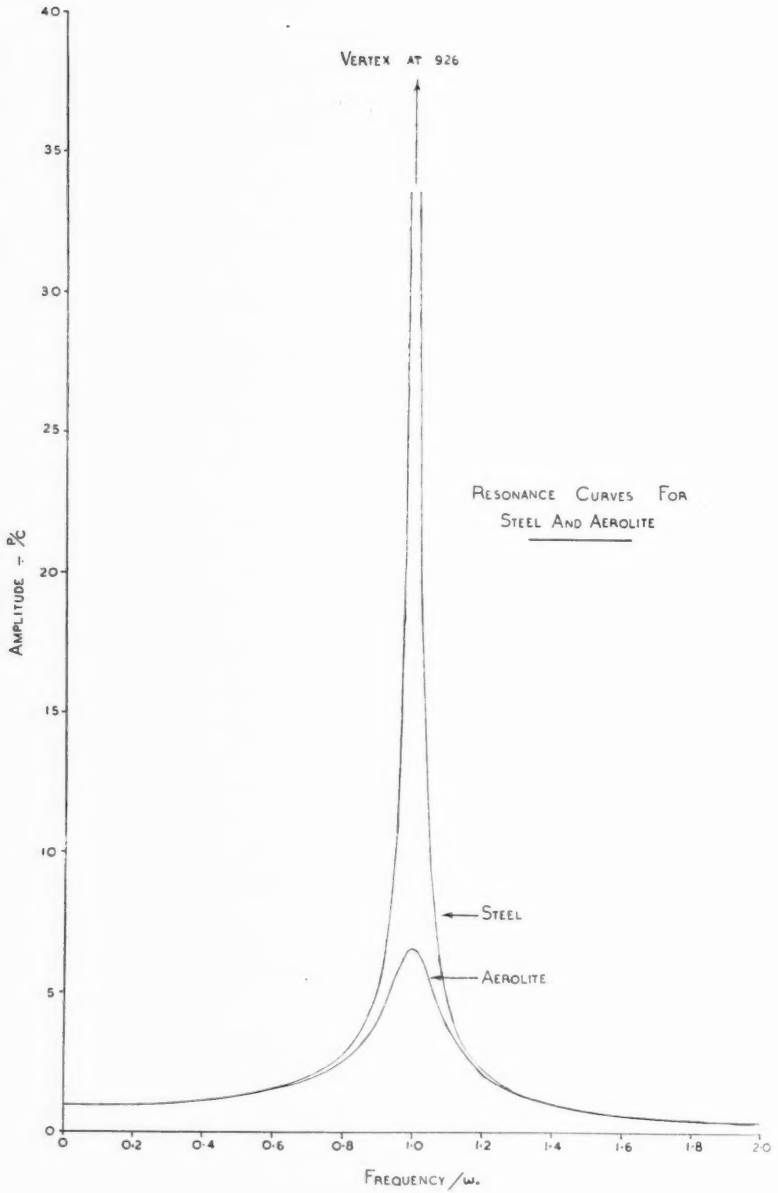


FIG. 21.

Comparative response of steel and aerolite in forced vibration.

the components, nevertheless the results obtained showed that the torsional damping (where energy absorption in the material may be expected to predominate) of a metal monoplane wing was about one-fifth of that of a wood monoplane wing.

Effect of Energy Absorption on Torsional Shock.

The beneficial effects of high energy absorption can also be illustrated by considering a member such as an airscrew blade which is free at one end and is given a sudden twist at the other. The effect of the sudden twist will be to send a torsional wave down the member; this torsional wave will be reflected at the free end (tip of the airscrew blade) and will return to the fixed end with practically undiminished energy if the material has small energy absorption. As the free end and the fixed end form an antinode and a node respectively the original and reflected waves will interact to produce a maximum stress at the fixed end of twice the value which would obtain in the absence of reflection.

If, however, the material has finite energy absorption the reflected wave will return with diminished energy and the maximum stress will be correspondingly reduced.

Now let us disregard considerations of energy absorption and treat aerolite as a metallic material. The maximum shear stress (56) q developed if a circular shaft of radius r is suddenly given an angular velocity ω is given by

$$q = r\omega\,(G\rho)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Thus the ratio of shear stresses developed in airscrew blades of duralumin and aerolite will be

$$[(G_{\mathrm{D}}\rho_{\mathrm{D}})/(G_{\mathrm{A}}\rho_{\mathrm{A}})]^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Putting

$$\rho_{\mathrm{D}} = 2.85 \qquad G_{\mathrm{D}} = 4.2 \times 10^{6}$$
$$\rho_{\mathrm{A}} = 1.34 \qquad G_{\mathrm{A}} = 0.35 \times 10^{6}$$

the ratio of shear stresses in duralumin and aerolite will be found to be 5 : 1. This is also about the ratio of the shear strengths of the materials. Even on this basis of comparison, therefore, aerolite is seen to have a high resistance to torsional shocks.

Effect of Energy Absorption on Wing Flutter.

The effect of damping, due to internal energy absorption, on wing flutter has been investigated by H. G. Küssner (55) and R. Kassner (57). In general we should expect such energy absorption to raise the critical speed at which flutter takes place, because the energy thus used up has to be supplied by aerodynamic forces. It is only, however, when the ratio of torsional to bending stiffness is low that energy absorption has any marked effect. In monoplanes the ratio is high and energy absorption has no considerable effect.

As will be seen later, although an aerolite wing would necessarily have a low bending stiffness it can be made (weight for weight) to have a greater torsional stiffness than a metal or wooden wing. The energy absorbing powers of aerolite would not therefore have any marked effect on the critical speed, but since the critical speed is primarily dependent on the ratio of torsional to flexural stiffness, such an aerolite wing should have a higher critical speed than a wing of wood or metal of equal weight.

The Creep of Aerolite.

In addition to elastic hysteresis bakelite and aerolite also show "elastic after effect." That is to say, when a stress is applied the strain does not instan-

taneously reach its limiting value. The magnitude of this elastic after effect increases with the stress, but it can be detected in cord aerolite at stresses as low as 500lbs./sq. in. This after effect is largely reversible and becomes very nearly so after the load has been applied and removed four or five times.

The irreversible component of the creep becomes more noticeable at high stresses. Even at 6,000lbs. per sq. inch, however, in cord aerolite, the irreversible component practically disappears after four or five successive loadings and unloadings. We hope to study the creep of bakelite and aerolite in greater detail in the near future.

The Fatigue Characteristics of Aerolite.

1. *Static Fatigue.*

The strength of aerolite is greater under constant loads of short period than under loads applied for a long time. Fig. 22 shows results obtained by the

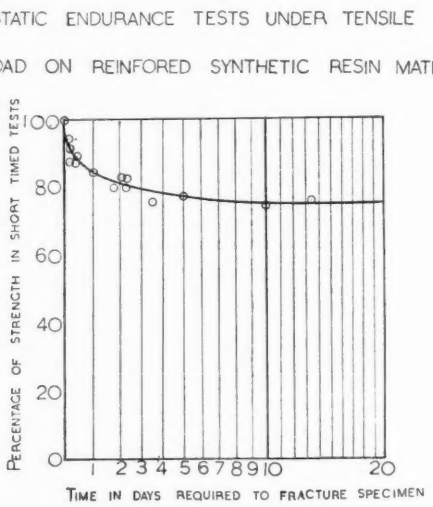


Fig. 22.

de Havilland Aircraft Company, Ltd., on the variation of tensile strength with time during which the load is applied. It will be seen that there appears to be a static fatigue limit at about 75 per cent. of the strength to instantaneous loads.

Wood (58) behaves in exactly the same way as is shown by Fig. 23 (see also Ref. 59).

2. *Dynamic Fatigue (Wöhler Tests).*

Since the process of static fatigue must be going on during the time taken to carry out dynamic fatigue tests, the determination of the dynamic fatigue limit (if it exists) is difficult. The fact that the fatigue limit as determined by dynamic tests seems to be somewhere about the same as the static limit suggests that perhaps only a static limit exists. The behaviour of aerolite in rotating beam tests is certainly very different from that of metals, because it is possible, as both G. Parzich (51) and Gough and Cockroft (60) have pointed out, for the

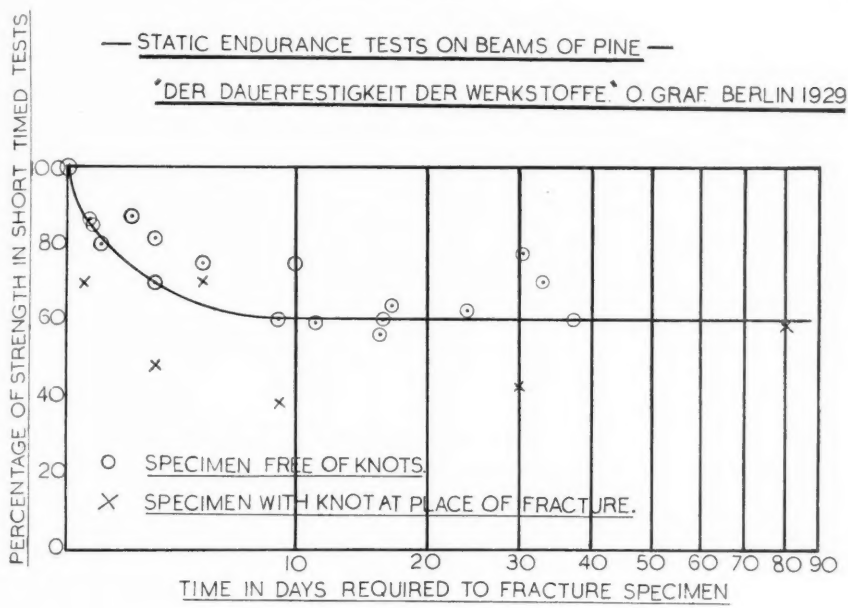


FIG. 23.
Static fatigue of pine.

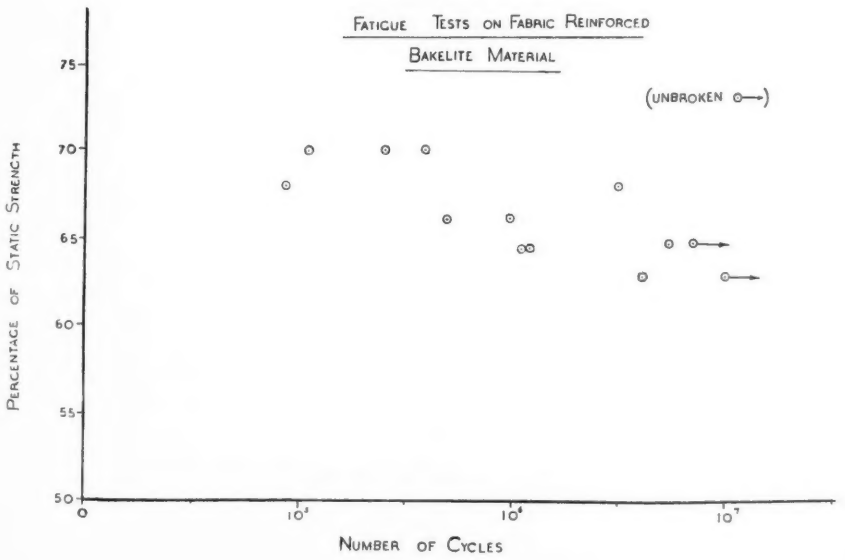


FIG. 24.
Wöhler fatigue tests on aerolite (coarse grade).
Reproduced by courtesy of Messrs. G. S. Gough and N. W. W. Cockcroft.

specimen to continue to hold together for many millions of revolutions after a split has first appeared. The amorphous character of the material seems to prevent any violently progressive crack formation.

A difficulty in the interpretation of rotating beam tests is to know what stresses are being caused by the applied bending moment. The stress-strain characteristics of the material make the ordinary Navier relation invalid and in addition energy absorption will reduce the magnitude of the alternating stress.

Gough and Cockroft (60) obtained the results shown in Fig. 24, indicating the existence of a fatigue limit at about 60 per cent. of the instantaneous static strength. The speed of rotation was 1,000 r.p.m. so that 10^7 cycles corresponds to nearly seven days—a period of time sufficient for static fatigue to make itself apparent. O. Kraemer (61) found the fatigue limit to be 35 to 40 per cent. of the instantaneous static tensile strength. G. Parzich (51) found the torsional fatigue limit to be 50 ± 10 per cent. of the static torsional strength. It is possible that the moulding pressure may affect the fatigue limit since initial compression, at least in brittle metals, raises the fatigue limit (62).

3. *Impact Fatigue.*

We have compared the behaviour of specimens of the same shape and size of aerolite, R.R. 56 alloy, duralumin, and Y alloy, under repeated impact tensile loads, using an Amsler repeated impact testing machine. These results, together with others obtained by Messrs. High Duty Alloys, Ltd., and reproduced by their kind permission, are shown in Fig. 25. It will be seen that the fatigue limit in impact is about the same for aerolite cord as for R.R. 56. These results emphasise the ability of aerolite to resist shock.

Actually they are in accordance with elementary considerations of the process of impact. Let K be the kinetic energy of the hammer on striking a specimen of length l and area A. The strain energy produced in the specimen will be $E\lambda^2 A/2l$, where E is Young's Modulus and λ is the extension.

Provided no energy escapes from the specimen

$$K = E\lambda^2 A/2l \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The maximum tensile stress p in the specimen will be $E\lambda/l$.

Thus

$$K = p^2 l/E \,.\, A/2$$
$$K = p^2 lA/E$$

or

$$p = \sqrt{(KE/lA)} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The maximum stress developed is therefore proportional to the square root of the elastic modulus. The ratio of the stresses set up in R.R. 56 and aerolite by a given energy of impact will therefore be $\sqrt{10.6/2.0} = 2.3$. Taking the strength of aerolite as 26,000lbs./sq. in. this would give the strength of R.R. 56 as 26.7 tons/sq. in. which is of the right order of magnitude.

Of course, a great deal of the energy of impact escapes from the machine as is evident from the vibration set up in the floor. When testing aerolite specimens there is a considerable decrease in vibration for the same impact energy due to the energy absorbing properties of the material.

Resistance of Aerolite to Corrosion.

We have not carried out any systematic experiments on the resistance of aerolite to attack by chemical agents, but the following tests carried out at the D.V.L. (61) on bakelite reinforced with paper and with fabric show what may be expected.

1. *Water Absorption.*

Test specimens were immersed in water for 24 hours. Paper-filled specimens showed the greatest water absorption with 0.85 per cent.; the pure resin showed

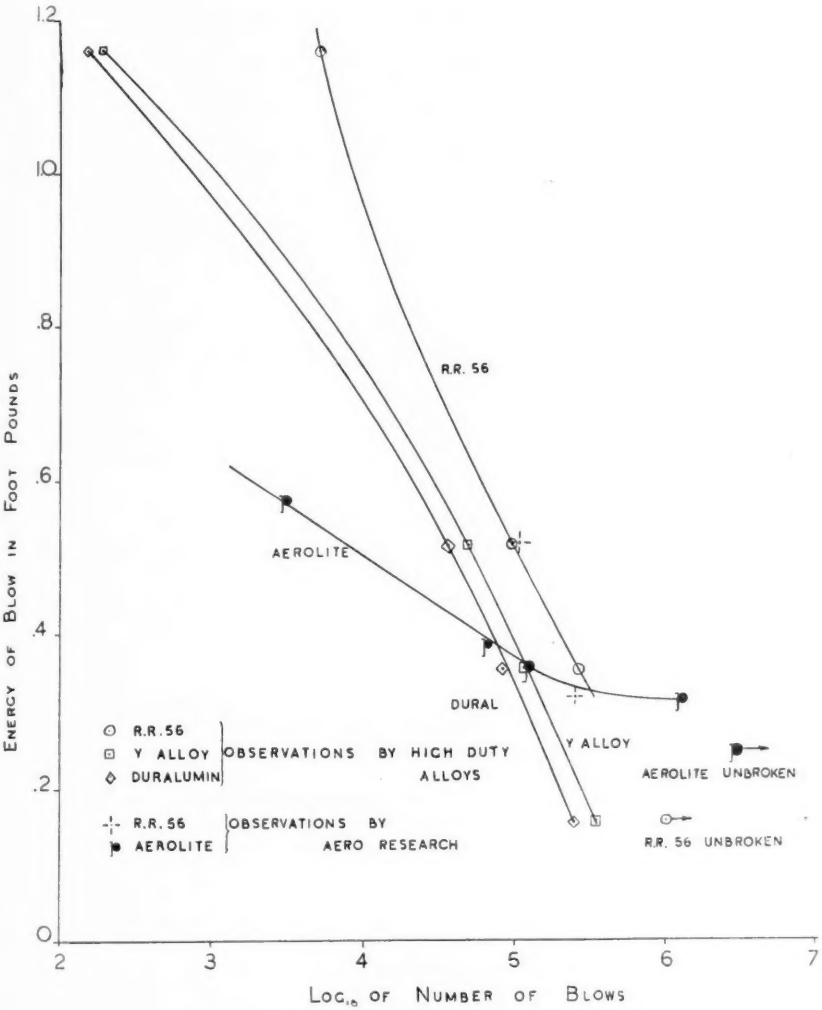


FIG. 25.
Comparative impact fatigue characteristics.

practically zero absorption. It appears that the greater the proportion of resin, the greater is the resistance to water.

2. *Weathering Tests.*

The first signs of weathering in specimens were noticed after about three months in a 1 mm. paper-filled specimen, which showed fraying at the edges. After six months the surface, originally smooth, of the majority of the specimens had become matt. The edges of 1 mm. paper-filled material showed distinct disintegration. At this stage, however, there was no diminution in the strength properties.

After 15 months it was observed that some of the specimens had become somewhat bleached by the action of strong sunlight. The fraying of the thin paper material, due chiefly to the mechanical action of dust and rain, had proceeded further. The strength reduction of these specimens amounted to 14 per cent.; in the case of the thick fabric-filled boards, there was hardly any reduction in strength. In the test pieces the area of edges constituted a large proportion of the total surface of the specimen. It is just these surfaces which are especially sensitive to the effects of weather and damp. The effect of weathering on specimens of larger size should therefore be much less.

By repeated bending of several of the test pieces it was shown that the flexibility of the material had in no way been impaired by the weathering process.

3. *Resistance to Sea Water.*

The tests were carried out in tanks in which a 3 per cent. solution of common salt was agitated. Alterations in surface, weight, and strength were studied. There was no alteration in surface of the fabric material after eight months; on the other hand, the paper material frayed slightly at the cut surfaces after one month, but this was so small that even after eight months it could hardly be detected by eye. Strength tests after eight months' immersion showed that the paper material had lost 12 per cent. of its original strength while the fabric material after drying had suffered no loss.

4. *Effect of Oil and Petrol.*

Fabric and paper specimens 1 mm. thick hung in a petrol benzene mixture for 10 days, then exposed to air for three days, showed no change in appearance or loss in strength properties. Specimens were also immersed in motor oil for 10 days without effect.

5. *Heat and Fire Resistance.*

Commercial synthetic resins are generally guaranteed up to 150°C. At 200°C. paper-filled material began to char, while the fabric material after a long time changed slightly in colour. Test pieces 100 × 100 × 1 mm. were held over a bunsen burner so that the edges were not in contact with the flame. After 15 seconds the upper surface of the fabric material swelled up suddenly, and after 20 seconds began to burn with much smoke. The flame was immediately extinguished on removal of the bunsen burner. The paper material behaved similarly; on removal of the burner it glowed weakly, and was immediately extinguished by the slightest draught. By comparison, a piece of plywood blazed up after 20 seconds.

GLUED JOINTS.

The problem of glueing or cementing aerolite is one of fundamental importance because the development of a successful method would enormously simplify the construction and repair of aircraft structures. Riveted or bolted joints can, of course, be made, and much more easily and effectively than in wood, but any kind of joint which involves the making of holes must be inferior to a practical method of glueing.

Our knowledge of the action of glues is small and mostly empirical. But there is evidence (63) that the strength of a glued joint depends on

(1) A mechanical interlocking between the cement and the material to be joined.

(2) A specific adhesion due either to primary or secondary bonds between the cement and the material.

Concerning (1) it should be noted that though microphotographs (64) of cemented joints between veneers of plywood show that it is not necessary that the cement should penetrate far into the wood, the smooth glass-like surface of aerolite

effectively prevents any kind of mechanical interlocking. As regards (2) the amorphous structure of aerolite provides few anchorages for primary bonds.

H. Stäger (65), of Messrs. Micafil A.G. of Zurich, has carried out an investigation on the tensile strength of cemented joints between smooth surfaces which is of great significance in regard to (2). His results are shown in Fig. 26. It will be seen that phenol formaldehyde resin at first gives strong joints, but that as polymerisation or condensation proceeds the strength falls off because of the decrease in the number of available bonds. Long continued heating causes a gradual recovery of tensile strength due probably to the fact that the bonds causing cross linkages have time to make themselves effective. Cresol resins show a less marked variation in strength with time, while shellac (in which heating can in time produce some cross-linking) shows a steady rise in strength.

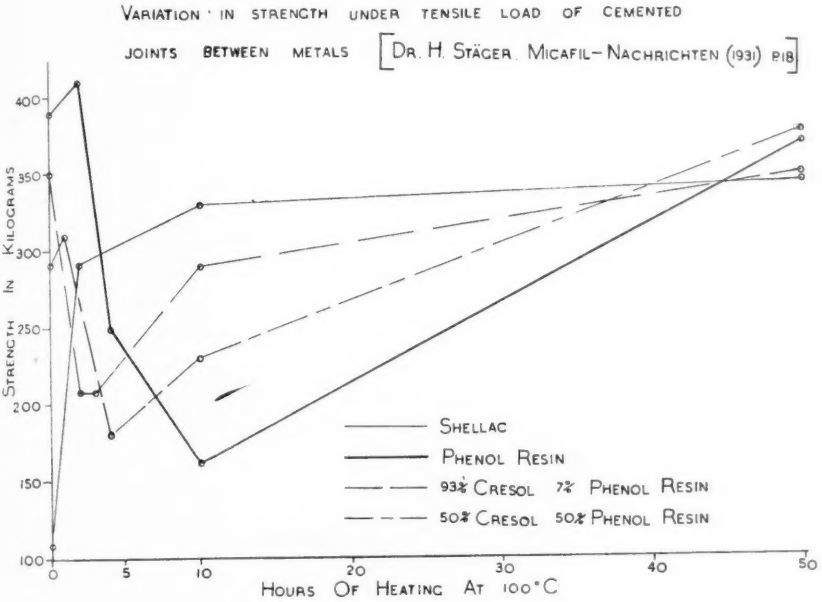


FIG. 26.

Effect of time of curing on tensile strength of cemented joints.

It is also relevant in connection with the existence of specific adhesion that gelatine (animal glue) loses its strength when the free amino groups are made to disappear by the action of formaldehyde (66).

We have carried out a number of investigations to obtain a good specific adhesion between fully cured aerolite using all the common cements and then adding strongly polar compounds. The results were disappointing. We then tried etching the aerolite in such a way as to break up the phenol formaldehyde structure, but to leave the cotton reinforcement untouched. We have not yet had time to carry out any extensive investigations, but some of our results, such as they are, are reproduced in Fig. 27. In the light of these results we believe that the problem of making cemented joints and of building up structures *in situ* can be regarded as solved in principle. We have also obtained good results by sandblasting and have constructed a simple device by which the fabric can easily be exposed along the directions in which the glued joint is to be made.

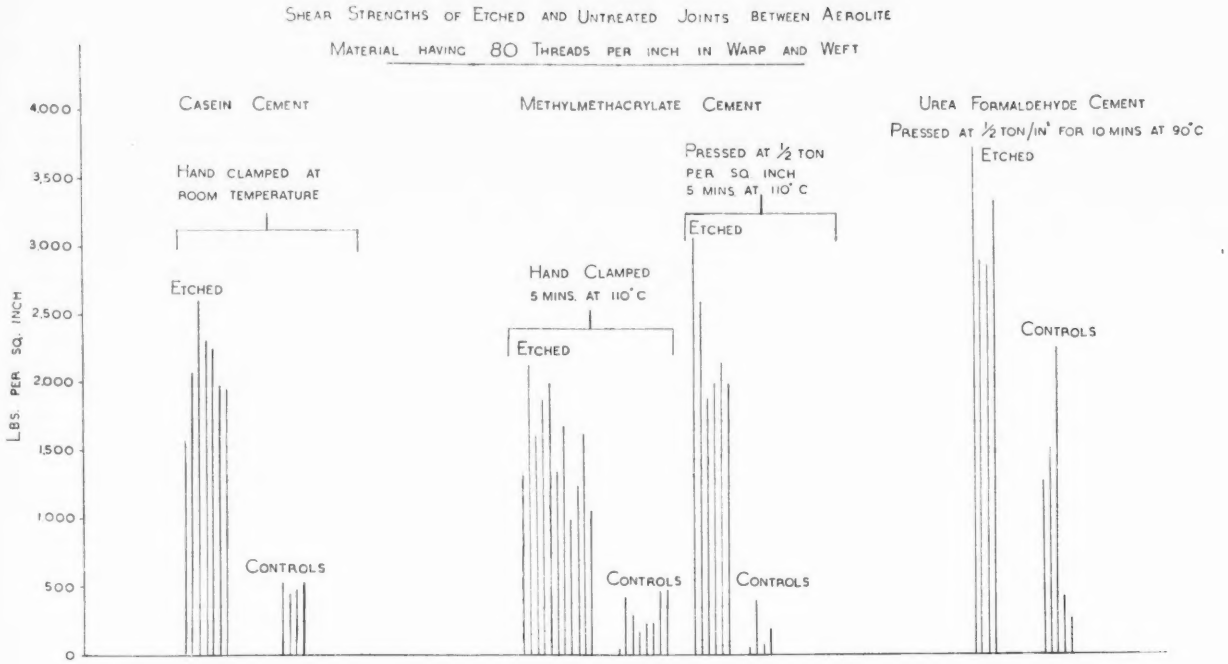


FIG. 27.

Effect on strength of glued joints of etching aerolite.

BOLTED JOINTS.

A fundamental rule in aircraft design is to avoid as far as possible the use of fittings and connections; how far and with what success that rule can be applied was first brought home to me after a close examination of a Fokker machine. But some fittings and bolted joints are unavoidable.

Results on some tests on bearing strength are shown in Fig. 28. In these

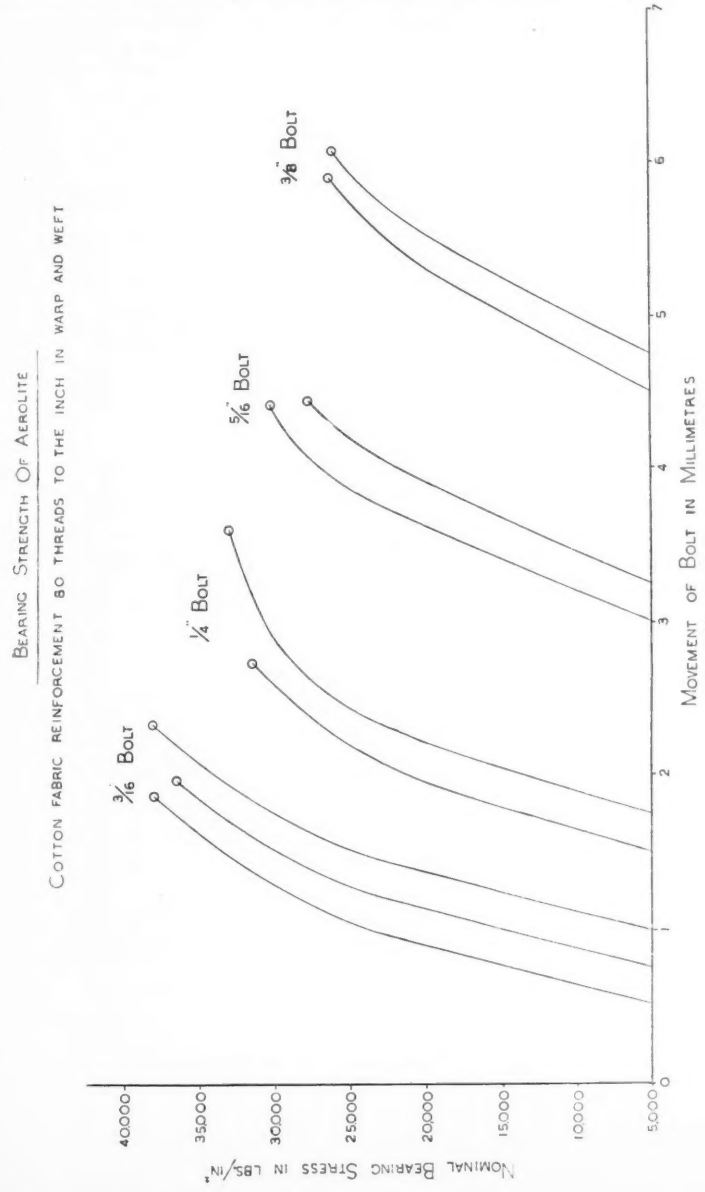


FIG. 28.

Bearing strength of aerolite.

tests the material was sufficiently thin to prevent any deformation or bending of the bolt under load; they represent pure bearing strength unaccompanied by any frictional contribution such as always exists in practice. Roughly speaking, the bearing strength is over five times greater than spruce along the grain and about forty times greater than spruce across the grain. One of the great troubles in making bolted connections in wood is the low shearing strength which necessitates a large separation between the bolts. In aerolite a much closer spacing can be used. The strength of such joints is dependent not only on the bearing stresses in the holes, but also on the amount of friction between the metal fitting and the wood or aerolite. The low compressive strength of wood perpendicular to the grain and the possibility of shrinkage make the attainment of any considerable amount of friction difficult and uncertain. In aerolite, however, the great hardness of the material (particularly perpendicular to the layers of reinforcement) allows considerable frictional forces to be set up.

The mean bearing strengths for the bolt diameters shown in Fig. 28 are given in Table VII below.

TABLE VII.

BEARING STRENGTHS.

Diameter.	Bearing Strength, lbs. per sq. in.
$\frac{3}{8}$in.	26,300
$\frac{5}{16}$in.	29,400
$\frac{1}{4}$in.	31,500
$\frac{3}{16}$in.	37,000

These figures refer to short bolts. The permissible bearing stress will decrease with increase in length of the bolt (67).

These results show that the apparent maximum bearing stress is less with large diameter bolts than with small ones. The conception of a bearing stress equal to the applied load divided by the projected bolt area is, of course, a convenient but crude one, quite unrelated to the stresses which in fact are set up. Actually the maximum load appears to be proportional to the square root of the bolt diameter as shown in the table below.

TABLE VIII.

Maximum Load, L lbs.	Diameter of Bolt, D ins.	$L/D^{\frac{1}{2}}$
1,250	$\frac{3}{8}$	2,040
1,117	$\frac{5}{16}$	1,998
1,000	$\frac{1}{4}$	2,000
883	$\frac{3}{16}$	2,040

PART II. APPLICATIONS.

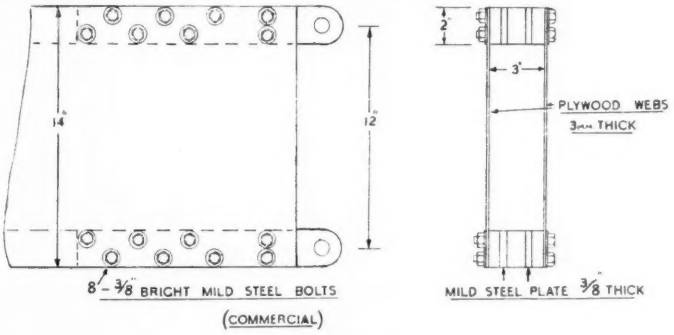
MONOPLANE WING ROOT JOINTS.

The most troublesome joints in an aircraft structure are the attachments of the outer wings to the centre section. In a cantilever machine the bending moments at the wing roots are extremely high and necessitate the use of heavy fittings with numerous bolts. As an example we may consider an aeroplane of one ton gross weight. The factored bending moment at the front spar joint, after allowing for all relief loads, might be 285,000lbs ins. with a shear load of 3,400lbs. Airworthiness requirements stipulate that at a load of 62.5 per cent. of the full load there shall be no permanent set. The distance between the top and bottom attachments might be 12in. resulting in a factored load in the top and bottom flanges of 23,750lbs. (10$\frac{1}{2}$ tons). Assuming the spar to be 3in. wide we should require, say, eight $\frac{3}{8}$in. bolts in each flange; thus in the centre section front spar there will be 32 bolts. Taking into account the rear spar and the

outer wings we shall need one hundred and twenty-eight bolts. These bolts could be lightened with $\frac{5}{16}$in. holes, but even so the weight of the front and rear spar centre section bolts alone amounts to 7.76lbs.

A saving in weight can be obtained by using aerolite for the spar ends, not only through the reduction made possible in the number of bolts and the size of the fittings, but also through the reduction in the sizes of packing blocks. These aerolite ends could be glued with a spliced joint to the wood; but for the centre section, which might be only three feet wide, it would hardly be worth while making such glued joints and it would be better to use aerolite entirely for the centre section spar. The spar width could then be reduced to 1in., thus reducing the length of each bolt to one-third. Due to the more uniform bearing pressure along the length of the bolts the fittings could simply be held on to each side of the spar instead of in saw cuts as in the wooden centre section. The reduction in flange area also makes possible an increase in the distance between top and bottom attachments with a consequent reduction in the forces produced by the applied bending moment.

Sketches of the different methods of construction are shown in Figs. 29 and 30. Details of the weights are given below. As an equal saving in weight should result for the rear spar the total saving in weight should be 24lbs.



JOINT IN WOOD CENTRE SECTION

FRONT SPAR

FIG. 29.

WEIGHT OF WOOD CENTRE SECTION (FRONT SPAR).

Eight steel plates (by weighing)	8.80 lbs.
32 drilled bolts (by weighing)	3.30 ,,
32 nuts	0.58 ,,
Plywood	3.25 ,,
Spruce flanges and packing	7.09 ,,
Stiffeners	1.50 ,,
	24.52 lbs.

WEIGHT OF AEROLITE CENTRE SECTION (FRONT SPAR).

Eight steel plates	1.83 lbs.
16 $\frac{5}{16}$in. solid bolts (1.2in. long)	0.50 ,,
Nuts	0.11 ,,
Webs	2.87 ,,
Aerolite flanges and packing	2.64 ,,
Stiffeners	4.0 ,,
	11.95 lbs.

AEROLITE FOR SHEAR BRACING.

We have seen that the high bearing strength of aerolite makes possible a considerable saving of weight in components where bearing loads predominate. But this is not the only instance where the use of aerolite can effect a considerable saving in weight. A special type of reinforcement makes it possible to obtain both increased stiffness and increased strength for a given weight (or alternatively reduced weight for an equal stiffness or strength) in torsional and vertical shear in comparison with alclad or plywood as ordinarily used.

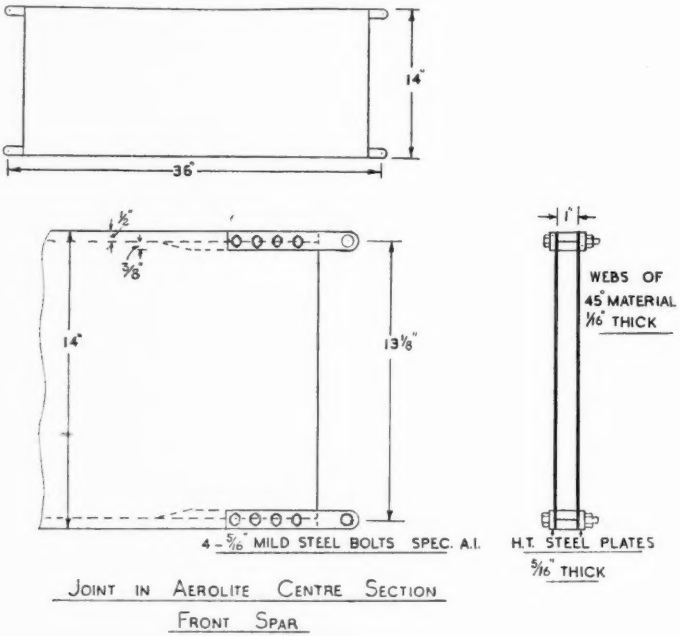


FIG. 30.

Because of the great importance of torsional stiffness in modern aircraft, I believe that this is one of the applications of aerolite of most immediate interest to designers. As is well known, the critical flutter speed of a wing is in general determined not by the separate magnitudes of flexural and torsional stiffness, but by the ratio of torsional to flexural stiffness and the greater this ratio the higher is the critical speed, provided the centre of gravity lies behind the elastic axis (68).

The method of making aerolite to give a high torsional strength and stiffness is to fold and press the fabric in such a way that the warp and weft are parallel to the lines of principal stress.

Plywood can, of course, be made also with the plies at 45° to the edge of the sheet, but the material is expensive and considerable waste is incurred in its production.

In most aircraft structures the ratio of shear load to depth of structure is such that we are concerned only with Wagner beams in which the web is in a state of tension at about 45° to the necessary stiffeners (69). Thus in comparing the relative merits of plywood and aerolite the proper bases of comparison for strength and flexibility are the tensile strength and the Young's Modulus respec-

tively measured at 45° to the edge of the sheets. It can be shown that the factor governing the torsional stiffness of a structure made from thin sheet with stiffeners is not G (the rigidity modulus) which ceases to have a meaning in such cases, but $E/4$ where E is the value of Young's Modulus at 45° (70).

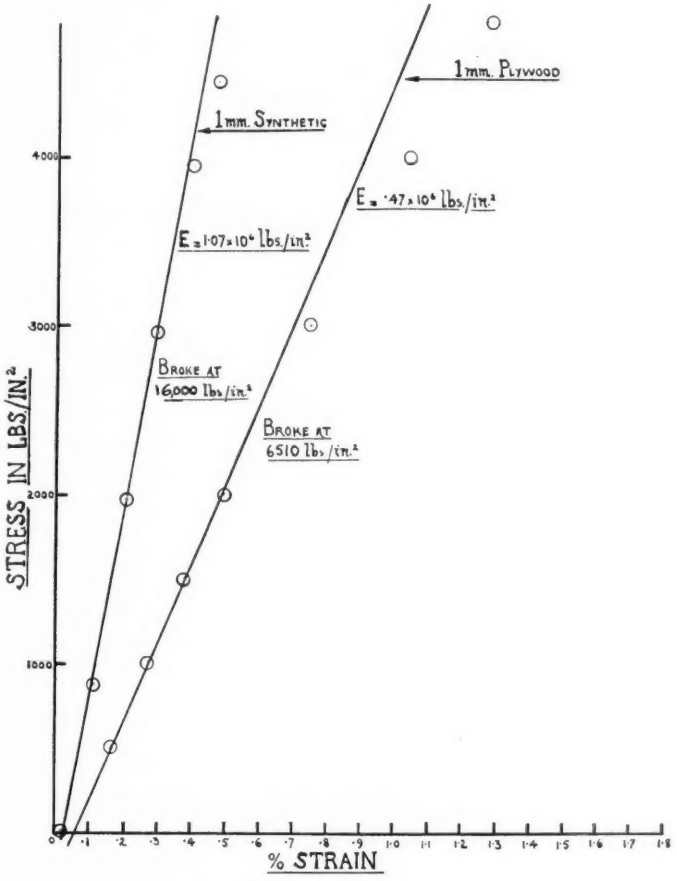


FIG. 31.

Stress-strain curves for special aerolite material and for plywood at 45° to the grain.

Fig. 31 shows comparative stress-strain curves for 1 mm. three ply to specification 3V4 made with " Tego " cement, measured at 45° to the grain, and also for the special aerolite material. It will be seen that the stiffness is increased 2.3 times, the strength 2.5 times and the weight 1.7 times by the use of aerolite instead of plywood of the same thickness.

COWLINGS OF AEROLITE.

The primary requisite of cowling is stiffness, the second, freedom from liability to fatigue failure. It can easily be shown that for equal weight aerolite can give

the same stiffness as duralumin; the static strength of the aerolite will, however, be greater, as also will the energy absorption.

Consider a rectangular plate simply supported on all its edges under a uniformly distributed load w lbs. per sq. in.

Then the deflection is given by (71)

$$\delta_1 \propto \omega a^4/Et^3 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where a = length of the shorter side.
E = Young's Modulus of the material.
t = thickness of the sheet.

Then for equal stiffness of aerolite and duralumin plates of the same dimensions, but different thickness,

$$wa^4/E_A t_A^3 = wa^4/E_D t_D^3 \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where E_A, t_A, and E_D, t_D, refer to the elastic modulus and thickness of aerolite and duralumin respectively. The ratio of corresponding weights W_A and W_D will be

$$W_A/W_D = \rho_A t_A/\rho_D t_D \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Substituting values for E_A and E_D we get

$$W_A/W_D = (\rho_A/\rho_D)\ (E_D/E_A)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Putting $\rho_A = 1.34$, $\rho_D = 2.85$,

$$E_A = 1.1 \times 10^6,\ E_D = 10.5 \times 10^6,$$
$$W_A/W_D = (1.34/2.85)\ (10.5/1.1)^{\frac{1}{2}} = 1.0$$

Hence for equal stiffness the weights of duralumin and aerolite are equal.

On the other hand, the ratio of strengths for equal weights will be

$$P_A/P_D = (p_A/p_D)\ [\rho_D/\rho_A]^2 \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where p_A and p_D are the ultimate strengths.

Putting $p_A = 16{,}000$lbs. per sq. in., $p_D = 56{,}000$lbs. per sq. in.

$$P_A/P_D = 1.26$$

Half hard aluminium is frequently used for cowlings. This material has the following characteristics:—

$$\rho_{A1} = 2.705,\ p_{A1} = 18{,}000\text{lbs./sq. in.},\ E = 10.1 \times 10^6\text{lbs./sq. in.}$$

This gives for equal stiffness

$$W_A/W_{A1} = (1.34/2.705)\ [10.1/1.1]^{\frac{1}{2}} = 1.0$$

For equal weight the ratio of strengths of aerolite to that of aluminium will be

$$P_A/P_{A1} = (16{,}000/18{,}000)\ [2.705/1.34]^2 = 3.6$$

Thus the material should be far less liable to develop troublesome fatigue cracks than aluminium.

The following table summarises the above results and includes figures for electron sheet:—

TABLE IX.

COMPARISON OF AEROLITE WITH SOME OTHER MATERIALS FOR COWLING.

Material.	Ratio of weight of aerolite to weight of material for same stiffness.	Ratio of strength of aerolite to strength of material for same weight.
Duralumin	1.0	1.26
Aluminum (half hard)	1.0	3.6
Electron sheet ...	1.37	0.80

These results are of greater significance than appears at first sight, because so often the thickness of an aeroplane covering is determined not by the structural loads but by its strength under handling loads ("Griffestigkeit"). Thus

the covering of a fuselage is often made much thicker than is required by flying and landing loads, because it has to be capable of resisting handling loads applied at right angles to the plane of the sheet.

AEROLITE IN STRUCTURES.

Although the strength of aerolite in relation to its density can compare favourably with the values for other materials, a comparison on the basis of Young's Modulus divided by density suggests that for equal weights the aerolite will result in a far less rigid structure. Some representative figures are given below.

TABLE X.

Material.	Tensile Strength, tons/sq. in.	Compressive Strength, tons/sq. in.	Specific Gravity.	E lbs./ sq. in.	Tensile Strength $/\rho$	Compressive Strength $/\rho$	E/ρ
High tensile steel	90	—	7.92	30.0×10^6	11.4	—	3.8×10^6
Spruce	4.5	2.2	0.45	1.5	10.0	4.9	3.3×10^6
Duralumin ...	25	25	2.85	10.5	8.78	8.78	3.7×10^6
Aerolite cord ...	11.6	11.2	1.34	2.0	8.66	8.4	1.5×10^6

Actually, however, this is not a proper basis of comparison of stiffness or of strength, because both involve not only constants characteristic of the material but also of the geometrical features of the structure. No general basis of comparison is therefore possible, and we must specify in each case the type of structure considered and what quantities are to be regarded as variable. In aircraft, aerodynamic considerations often fix external dimensions and the designer is able to vary internal dimensions only. Thus, in a wing or fuselage the external dimensions can generally be regarded as fixed and the thickness of the covering as variable. We will now consider a few particular cases where the use of aerolite may be advantageous.

(*a*) FLAT PLATE IN COMPRESSION (E AND t VARIABLE).

The critical stress of an isotropic flat plate in compression is (72)

$$p_c = kE\,(t/b)^2 \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Thus for equal strengths of plates of same dimensions, but different thicknesses,

$$E_1 t_1^3 = E_2 t_2^3 \quad . \quad . \quad . \quad . \quad . \quad (21)$$

The ratio of weights will therefore be

$$W_1/W_2 = (\rho_1/\rho_2)\,[E_2/E_1]^{\frac{1}{3}} \quad . \quad . \quad . \quad . \quad (22)$$

which is the same condition as for equal *stiffness* in cowling, *cf.* eq. (18). Comparing aerolite and duralumin

$$\rho_1 = 1.34,\ \rho_2 = 2.85,\ E_1 = 1.1 \times 10^6,\ E_2 = 10.5 \times 10^6.$$

Then $W_1/W_2 = 1.0$, *i.e.*, aerolite and duralumin have equal weights for equal strength.

(*b*) COMPRESSION OF A CYLINDER WITHOUT LONGITUDINAL STIFFENERS (E AND t VARIABLE).

$$p_c = 0.2\,E\,(t/R) + 3.3\,E\,(t/H)^2 \quad . \quad . \quad . \quad . \quad (23)$$

if the edges are held rigidly (73). Strength will therefore be given by

$$p_c 2\pi Rt = \pi E t^2\,(0.4 + 6.6\,Rt/H^2) \quad . \quad . \quad . \quad . \quad (24)$$

Putting $R = 40$in. and $H = 12$in. (so as to make conditions approximate to those of a fuselage such as that of the "Vultee" in which there are circular stiffeners, say 12in. apart, but no longitudinal stiffeners)

$$\text{Strength} = \pi E t^2 (0.4 + 1.83\, t) \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Since t will in general be of the order of 1 mm. the term $1.83\, t$ may be neglected. Thus the ratio of weights for equal strength will be

$$W_1/W_2 = \rho_1 t_1/\rho_2 t_2 = (\rho_1/\rho_2)\ (E_2/E_1)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (26)$$

Comparing normal aerolite and duralumin

$$W_1/W_2 = (1.34/2.85)\ (10.5/1.1)^{\frac{1}{2}} = 1.44$$

If cord aerolite is compared with duralumin

$$W_1/W_2 = (1.34/2.85)\ (10.5/2.0)^{\frac{1}{2}} = 1.08$$

(*c*) Rectangular Strut of given Width (E and d variable).

To get some idea of the relative behaviour of aerolite and duralumin for longitudinal stiffeners we will assume the use of a simple rectangular section stabilised about its minor axis by the skin. Then from considerations of "Griffestigkeit" we should not use material in either case less than 1 mm. thick.

For equal stiffness

$$E_1 I_1 = E_2 I_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

or since

$$I_1 = b d_1^3/12,\ I_2 = b d_2^3/12$$

$$E_1 d_1^3 = E_2 d_2^3 \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

This condition is the same as for cowling. But whereas for cowling we should use aerolite with equal warp and weft for a stiffener it would be feasible to use cord material. The ratio of weights for equal stiffness would then be

$$(1.34/2.85)\ (10.5/2.0)^{\frac{1}{2}} = 0.817$$

(*d*) Beam of given Depth.

In a wing the depth of the spar is determined by aerodynamical considerations; the width of the flange is variable. In this case for a given strength in bending the ratio of weights for a given strength will be seen to be

$$W_1/W_2 = (\rho_1/\rho_2)\ (p_2/p_1) \quad . \quad . \quad . \quad . \quad . \quad (29)$$

For spruce $\rho_2 = 0.45$, $p_2 = 5{,}500$. For cord aerolite $\rho_1 = 1.34$, $p_1 = 25{,}000$. Thus

$$W_1/W_2 = (1.34/0.45)\ (5{,}500/25{,}000) = 0.655$$

On the other hand, in wing spars of spruce and aerolite designed for equal strength the spruce spar will be much stiffer than the aerolite, since the ratio of stiffnesses will be

$$E_1 p_2/E_2 p_1 = (2/1.5)\ (5{,}000/25{,}000) = 0.27$$

We have already noted, however, that the torsional stiffness of an aerolite wing can be greater than that of a wooden wing for a given weight. Thus the ratio of torsional to flexural stiffness can be greater for an aerolite than for a wooden wing.

Advantages of Low Density.

It will be seen from the above that generally a low density is more important than a high Young's Modulus (as was, I think, first pointed out by F. R. Shanley (74). A decrease in density, even though accompanied by a corresponding decrease in Young's Modulus, would therefore be beneficial. With this object in view we have carried out experiments to produce a light resin by giving it a

sponge-like structure and we find that the density can be reduced in this way to 0.3 without resulting in too friable a material.

Such a light material should make possible the use of very thick walls so that a pure stressed skin construction should be possible even in fuselages and wings of large diameter. Under these circumstances the second term, involving the square of the skin thickness, in equation (27), will become important and the strength will be increased at a rapidly increasing rate.

Aerolite Bearings.

Reinforced bakelite is used with great success for bearings under conditions of slow speed and great pressure. In rolling mills the use of this material has resulted in considerable economies both in power consumed, and due to the long life of such bearings (about 13 times that of metal bearings) (75) in replacement expenses. The bearings have the additional advantage of being "non-seizing;" should lubrication fail, the bearing gets hot and produces an intensely strong smell of burning phenol without damaging the shaft. Whereas it is not generally possible to start up under full load with metal bearings because of seizing troubles due to interruption under static load of the oil film, no such difficulties are found with aerolite. In addition, dust and dirt do not have the deleterious effect on shafts running in aerolite bearings that is observed when white metal or bronze is used.

Many fittings in aircraft are subjected to rather similar conditions of slow movement, very often reciprocating in character, and sometimes of considerable pressure, and it may therefore be advantageous to use bushings of aerolite instead of brass in control levers and the like.

Conversely the elimination of the necessity for metal bushings in aerolite fittings leads to a saving in weight, and in a control lever we have made (to replace one in metal where trouble had been experienced with corrosion) the saving in weight and cost was quite considerable. In c.p. aerolite airscrew blades the aerolite can be made to bear directly on to metal and the conditions of operation (slow reciprocating motion) are just those suited to such a combination.

Research has not yet reached a point where the precise field of utility of such bearings can be defined. Their low heat conductivity (about 1/500 of that of a metal) rules them out for operation in engines, for example, though bakelite with a graphite filler may be of service under conditions of high speed operation where the bearing loads are light.

The following values for the coefficient of friction were obtained for a surface pressure of 7.1 lbs. per. sq. in. (76) representing very light loads such as might be produced for instance in a "fair lead."

Table XI.

Material.	Lubrication.	Coefficient of friction for Synthetic Resin for increasing times of running in.			Comparative figures for coefficient of friction for brass.
Bakelite with Fabric Reinforcement	Dry	0.25	0.38	0.42	—
	Grease ...	0.14	0.12	0.12	0.10
	Oil	0.7	0.07	0.07	0.063
	1 part Oil 5 parts water	0.08	0.08	0.08	—
	Water ...	0.08	0.08	0.08	0.085
Bakelite reinforced with Fabric Snippings	Grease ...	0.10	0.11	0.15	0.10
	Oil	0.045	0.063	0.075	0.063
	1 part Oil 5 parts water	0.089	0.089	0.089	—
	Water ...	0.122	0.122	0.122	0.085

It will be seen that under normal conditions of lubrication (grease or oil) the use of reinforcement composed of moulded snippings of fabric gives results of about the same value as brass. The coefficient of friction apparently decreases hyperbolically with increase of bearing pressure for constant velocity. The optimum velocity appears to be about 1 metre per second (75).

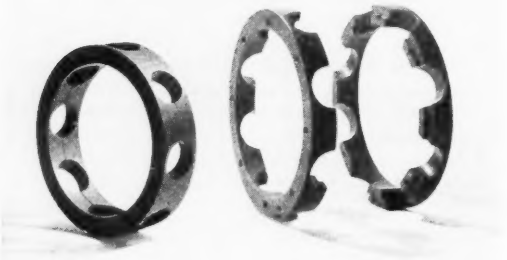


FIG. 32.
Ball races.

Ball and roller bearing cages are quite commonly made of synthetic material. Fig. 32 shows examples manufactured by Messrs. Ellison Insulations, Ltd.

SPINNING POTS.

Although not an aeronautical application the use of synthetic resin materials for spinning pots in the artificial silk industry is of interest, because of the severe

FIG. 33.
Spinning pot for viscose (artificial silk).

conditions under which they operate, and the similarity of these conditions to those affecting supercharger rotors. In such applications the material is required to withstand a certain velocity of revolution and the resulting stress will be directly proportional to the density. The low density and freedom from corrosion of bakelite makes its use particularly suitable for such conditions. Fig. 33 shows a spinning pot of wood-filled bakelite; below about 6000 r.p.m. (corresponding to a stress of 8000 lbs. per sq. in.) ordinary wood-filled bakelite can be used, but for greater speeds, tension reinforcement is required. We are at present engaged in improving the design and strength of these pots to allow higher working speeds.

AIRSCREWS.

One of the earliest applications of reinforced bakelite, was the construction in the United States of airscrews from impregnated and pressed cotton duck material. I believe that such airscrews were in use during the war 1914-1918 on " Liberty " engines. L. G. Nilson was granted a patent for such airscrews in 1919 (77).

The development of controllable pitch airscrews of aerolite is due in the first place to F. W. Caldwell and N. S. Clay, who, in N.A.C.A. Technical Notes Nos. 198 to 201 have given us an account of what may fairly be described as a brilliant engineering achievement. Fig. 34 shows their variable pitch airscrew with manual control which was capable not only of altering, but reversing the pitch.

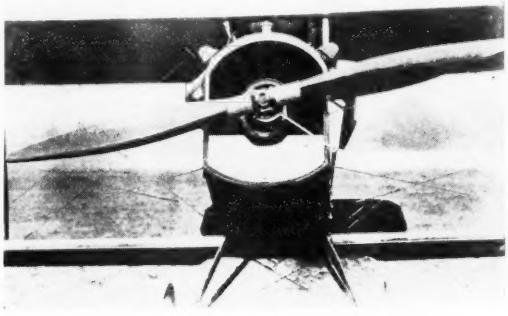


FIG. 34.
C.P. airscrew developed by F. W. Caldwell and N. S. Clay.

The stress at any section of an airscrew blade is a combination of tension due to centrifugal pull, and bending due to the aerodynamic thrust; there is also bending in a plane at right angles due to the aerodynamic drag force on the tip portion. Wooden blades, by virtue of their lower inertia forces, are much lighter than fixed metal blades, and the thicker sections give a slightly higher drag at the gain of a slightly better static thrust. With the advent of the controllable pitch propeller, this slight aerodynamic advantage of the wooden blade disappeared; but there remained with the metal c.p. screw very high centrifugal and inertia forces at the blade root which had to be carried under conditions of the utmost reliability in a rotating bearing. A hub so heavy was required, that many were of the opinion that at least for small aircraft the extra weight largely counterbalanced the possible increase in disposable load due to improvement in the take-off.

It will be seen that aerolite makes a very suitable material for controllable pitch airscrew blades. Its low density results in low centrifugal and inertia forces and consequently a light hub can be used. It has good energy absorption and fatigue characteristics, in particular it is free from corrosion fatigue; its notch sensitivity is such that there need be no fear of stress concentrations. For these reasons the de Havilland Aircraft Co., Ltd., in co-operation with Bakelite, Ltd., and Aero

Research, Ltd., are developing airscrew blades of this material. Fig. 35 shows such an airscrew for a Gipsy XII engine.

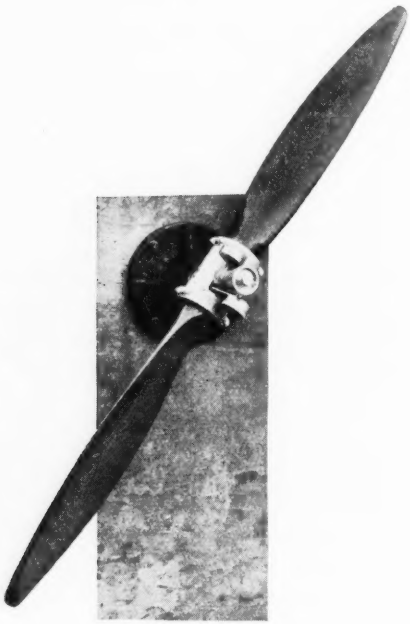


FIG. 35.
C.P. airscrew for Gipsy XII engine.

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Discussion.

The President: The author had spoken of the chief characteristics of plastic material in his most interesting paper and had chiefly had in mind the material which had been termed aerolite. Among those present were many who, in view of the immense impetus to aircraft construction to-day, were naturally looking for new materials wherever they could find them. There might be, perchance, some present who had already experimented in this direction and there would no doubt be many others who would have questions to put to the author which he might be able to answer out of the experience which he had already had.

Mr. M. LANGLEY (*Member*): The first thing which impressed him was the language difficulty. There were no doubt many chemists present who were quite familiar and happy with such terms as condensation, polymerisation, etc., but these were, perhaps, a little confusing to the engineer. On the other hand, he did not know how chemists got on with engineering terms like "resilience" and "strain energy." There was one word which completely defeated him, but he would like to know the meaning of the "syneresis." There was reference in the paper to the various stages of polymerisation which occurred in the resinoids, and certainly engineers would want to know if it were possible to get any sort of consistency in these materials and whether the same consistency could be obtained as in the manufacture of metals and whether it was possible to prophesy what was coming out of the pot when certain things in certain proportions were put in.

One set of curves (Fig. 26) dealt with cemented joints, and one of the curves rather puzzled him. This curve related to phenol resin and showed that when this material was tested over a period of time at about 100 degree C., there was a marked drop in strength, particularly at the end of 10 hours, to about one-third of the original strength. It would be interesting to know if that same phenomenon was repeated at other temperatures, as for example, in a completed aeroplane used under tropical conditions. There was a temperature under tropical conditions of perhaps 50 degrees C. combined with a period of hundreds or thousands of hours. If this showed an equally marked drop in strength, then it seemed to him to be a point for further research.

Another curve (Fig. 28) related to the strength of bolts. In this case the author had plotted the movement of a bolt in millimetres against bearing stress and the curves were carried down to a bearing stress of 5,000 lbs. per square inch, but he did not show what happened between zero and 5,000 lbs. per square inch. There might be a sudden turn below 5,000 lbs. per square inch.

A feature of aerolite was its strength under compression together with a certain weakness in tension, and the author had mentioned the analogy of reinforced concrete. Perhaps engineers might learn a great deal about the application of synthetic resins from the study of reinforced concrete methods, but he would like to know if any research had been carried out on other reinforcements than cord and fabric. Had a metal mesh been considered, and if so, what had been found out about it?

He had been interested in this subject for a long time, and what he had foreseen, perhaps rather optimistically, was the making of large components of aeroplanes in one piece. The author had shown that greater strength was obtained by increasing the bearing pressure and had gone to four tons, and perhaps higher, per square inch. But the higher the bearing pressure the more difficult it would be to make large mouldings, and that rather dashed one's hopes. Nevertheless, he felt sure that these difficulties would be overcome eventually and that ultimately it would be possible to mould large units.

With regard to tensile strength, he had heard it said that the tensile strength as shown in bend tests appeared to be considerably higher than the tensile strength of a single test piece—purely tensile test pieces—and he wondered whether the author had any information on that matter and could offer any explanation.

Mr. W. O. MANNING (*Fellow*): In Table V it was stated that the compressive strength of aerolite was 27,000lbs. per square inch perpendicular to the cords. He would like to know what the compressive strength was parallel to the cords because it seemed to him that it was this which really mattered.

It was just possible, continued Mr. Manning, that he might have been the first person to have used plastic materials in an aeroplane, which was 15 years ago. Many would remember that in the case of wooden wing machines the plywood used on the nose and the leading edge was a very great nuisance because it was always buckling, however carefully it was put on. He therefore used bakelite paper, which was then being used for electrical insulation. He started by making a frame of the shape of the leading edge and nose of an aeroplane and put some

bakelite paper on it. This frame was then put on the roof of a shop where it was exposed to sun and rain and snow and, in fact, all the elements. It was left there for six months and at the end of that time the material was as good as when it was new. There was not a bump or a kink in it. It was used afterwards on several machines, and was exceedingly successful. It was put on with wood screws which was easy with a wooden machine, but he also put a little glue between the bakelite paper and the wood, because although it did not hold very well it seemed worth while to do so to get a little additional strength.

Referring to the question of adhesion, Mr. Manning expressed the view that this is very little understood. The author was speaking of mechanical interlocking, but ordinary gum stuck exceedingly well to the smoothest plate glass and it was difficult to see how in a case of that sort there could be any question of mechanical interlocking. Certain other things such as cellulose acetate and cellulose itself could also be made to stick very well to glass and glue would also stick quite well. There were certain things which would not stick, but the question of getting some adhesive which would stick to this particular form of bakelite was, of course, extremely important.

In the case of a bakelite spar reinforced with dural, if this was used as a beam, the tension side would appear to be under a stress greater than the bakelite could support. It would follow that hair cracks must occur with probable entry of moisture into the spar. As a result, it appeared probable that the strength of the cords would rapidly disappear through bacteriological or fungoid actions, as in the similar case of the motor car type.

Mr. A. R. Duxton (Metropolitan-Vickers Electrical Co., Ltd.): He was fortunate in being associated with one of the largest research authorities in the country, and among things he had to do was to study materials. Therefore he had been greatly interested when he had heard of the new material aerolite. He would like to know, however, why this material had been christened "aerolite," because it was not really a new material, since it was apparently identical with the synthetic resin bonded fabric sheets already covered by British Standard Specification No. 668, which detailed the qualities of a laminated fabric board bonded with synthetic resin intended for the manufacture of gear wheels. By the selection of perhaps special fabrics, the tensile strength of this new material had been increased from the B.S.I. figure of 8,500lbs. to 25,000lbs. per square inch. If, however, high tensile strengths were desired, why use cotton when the reinforcement could be made by using a number of fine phosphor bronze wires which possessed a tensile strength of more than 60 tons, or even specially selected steel wires with a tensile strength of 160 tons, all of which could be embedded in a synthetic resin laminated board or actually woven into the fabric apparently used by the author.

In Table V, the tensile strength was given as varying between 18,000 and 25,000lbs., and the density was given as 1.34. If these figures were acceptable why not use densified wood with a similar density and a tensile strength of 35,000lbs., or even a Premix board possibly reinforced with fine wire mesh?

Later in the paper reference was made to the energy absorption of materials and it might be of interest to state that recent research had shown that it was possible to produce boards similar to aerolite with failure values ranging from 24,000ft.-lbs. to 240,000ft.-lbs., simply by the selection of the fabrics employed. A special testing machine produced by the Research Laboratories of the Metropolitan-Vickers Electrical Company, Limited, had been of exceptional use when conducting this investigation, and since the author did not have an opportunity of seeing this machine when he last visited the Metropolitan-Vickers laboratories, it would be interesting to know his opinion on the test results (of which Mr. Dunton had a slide), and whether materials which would withstand such drastic impacts were desired for aeroplane construction.

Towards the end of the paper reference was made to synthetic resin bonded fabric bearings, but when these were used for rolling mills it was interesting to

note that water instead of oil lubrication could be used. Here again, the endurance of this type of bearing varied very considerably, depending on the type of fabric employed. This emphasised the author's statement that this type of material was immune from corrosion. When dealing with new materials he sometimes wondered whether a new use could not be found for some of the new Premix boards which were of a material very much like cardboard, which could be bent to any shape and hardened by hot oil or heat. He could visualise such a material forming a covering for wings, cowlings and other parts of aeroplanes. All this simply tended to show that there were numbers of materials which could be applied to aeroplane construction, if the makers of such materials could only be made aware of what the aeroplane people required.

Dr. F. W. LANCHESTER (*Hon. Fellow*): He remembered, as a boy, seeing either in "Astra Castra" or in another favourite work, namely, Hartwig's "Aerial World," the word "aerolite" used in the same sense as "meteorite" and he wondered if this prior use of the word was unknown to the author of the paper. It was, he continued, very annoying to find words changing their personality in this way. For instance, in the early days the word "aerodrome" appeared in the dictionary as defined by Langley, namely, as a "flying machine," but whilst his "Aerodynamics" was in the press it came to be used to mean "balloon or airship shed," and by the time that book was in the hands of the public it had become "a landing ground," and in this sense it is still used. It is now understood to include the general equipment.

Referring to plastics, he said that 10 or 12 years ago he had a supply of bakelite reinforced with fabric from a firm in the United States, he believed that this was one of the first firms to manufacture it. That material would not stand heat. When tried for the timing gear wheels of a petrol motor it was not successful; exposed to a temperature of about 80 or 90 degrees centigrade, decomposition set in accompanied by a smell of phenol. From the same firm he obtained a roll of insulation material which became brittle and useless at normal temperature; again accompanied by a smell of phenol. He sent that back and the makers replaced it with something very little better.

This, he said, served to emphasise the great advance that had since been made in the production of these materials, and he heartily congratulated those responsible. He would like, however, to have some further information on the subject, *i.e.*, the cause of the early troubles and how these have been overcome.

Mr. I. J. GERARD (*Associate Fellow*): In the paper the author discussed the stress of an isotropic flat plate in compression. It was well known that a thin flat plate with no stiffeners was in itself able to carry only small compressive loads and in practice flat plates were reinforced with stiffeners to obtain an economic overall load carrying capacity. The load which produced instability of the plate was of little moment as the combination of plate and stiffeners carried much higher loads and collapse of the structure did not occur until the stiffeners buckled. If, however, one considered the manufacture of a type of fuselage or wing construction referred to in the paper, *i.e.*, a cylinder without longitudinal stiffeners suitable to withstand longitudinal compression, for which the class of material being discussed seemed suitable, one would probably use formula No. 23, omitting, as the author suggested, the second term, so that the failing stress would be assumed to be proportional to the product of Young's Modulus and the rates of thickness to radius of curvature. This formula had been found to fit closely a series of tests of curved duralumin panels and it would be interesting to make a corresponding series of tests of curved panels made of various reinforced synthetic resin materials.

From the figures given by the author in Table X, it appears that for a given weight, a duralumin structure will be about $2\frac{1}{2}$ times stiffer than one made of aerolite cord.

Mr. PHILIPPE: The author had referred to bakelite and aerolite purely as a means of distinguishing between the physical properties of the bonding material

alone and those of a material reinforced with a cotton filler, in order to show where the possibilities were of strengthening the material. He hoped the author would excuse him trying to make that clear, as the name Bakelite was a trade name well-known to many, covering a large range of materials incorporating different types of fillers.

If anyone wrote to Bakelite, Ltd., for a piece of bakelite they would not be given a material such as the author has referred to, but would be asked, what was it required for, as there is a large range of materials incorporating different types of fillers suitable for different purposes. There was a lot of work going on behind the scenes, and no conclusion had yet been reached as to what might still be added to the paper.

With regard to the possibility of metal reinforcement, such as wire mesh, the question was whether it was possible to get the necessary adhesion to the metal, so that the whole could be considered a united mass. If not, then surely the reinforcement was useless as the two parts were acting as separate bodies. If that were so, then one might almost do away with the bakelite or the bonding material and use the wire mesh alone.

There were a whole host of other questions that were likely to arise, but research work was being done, and in course of time further information would be available and he hoped would be made use of. From what the author had said, however, it would be agreed that a tremendous advance had been made in the possible use of these materials and that their possibilities have by no means yet been reached. As these materials became better known they would naturally receive greater attention, and it was hoped that manufacturers of aircraft and of synthetic resin products would co-operate together in order to help solve the problems which the author had outlined.

Mr. J. V. Connolly (*Associate Fellow*): About a year ago there was an article in *The Aeroplane* on the design of plastic wings and attention was drawn to the great possibilities of these materials, even in their then state of development. In the same article there was a suggested specification for bakelite suitable for aircraft construction. This called for a density of 1.33, a compressive strength of 40,000lbs., a tensile strength of 15,000lbs., and Young's Modulus of 2. That was a year ago, but the author had shown that already this specification could practically be fulfilled. Instead of a compressive strength of 40,000lbs., and a tensile strength of 15,000lbs., the author gave a uniform permissible stress which was almost exactly the mean of those two figures, and which was even more useful in that form. Further, the author had produced a Young's Modulus of 2.4 as against 2, and a density of only 1.34 as against 1.33. This indicated that if the conclusions in the earlier part of the paper were anything like correct, and if the estimate of the required improvement was also correct, by using very similar methods to those laid down in the article, a wing could now be designed which would show advantages over the ordinary form of construction. He believed the weight per square foot was something like 2.5lbs. for a machine with an aspect ratio of 8 and $N=7$, which would not be much below the average for such wings. The only thing that seemed to be greatly different in the suggested design was the fact that steel bar reinforcement was postulated. However, the question of adhesion had to be considered. In any case the steel bars did not now seem to be necessary because only sufficient steel bars were put in, to bring the tensile strength up to 40,000lbs., and obviously the cord material made a better reinforcement, weight for weight, than steel. At the same time he did not think it was altogether necessary to rule out the possibility of using steel reinforcement in the same way as it was used in concrete, and he imagined that the mathematical research already done on concrete would give a lead and show whether this was exactly true. Adhesion could be assured by using deformed bars. He believed that the properties of bakelite, even with the cord reinforcement, were not very different from those in cement concrete. Consequently, it should be possible to apply the theory for concrete design, which

had been very well developed, and was comparatively successful in so far as theoretical prediction was in agreement with actual tests.

Referring to glued joints, the curves in Fig. 26 gave the strength in kilogrammes, but that did not convey anything exactly unless the size of the specimen were known, or the results were given in kilogrammes per square cm. Referring to the author's own tests, which were on a subject of vital importance if built-up components had to be used, it would be of great interest to have further information. The author admitted that this was a very preliminary set of curves, and he wondered whether there was any time effect on the adhesion. He presumed that the casein cement had no interaction, chemically, on the bakelite and that therefore the only deterioration between the joint in the aerolite would be the normal deterioration of casein cement with time which, of course, could take place. The casein cement had definite advantages from a manufacturing point of view, but it was quite possible that one of the good hot propeller glues would be superior as they seemed to have quite good properties when used with more or less similar materials to bakelite. For example, a good propeller glue would take a piece out of a sheet of glass, and he imagined that unless there was some extraordinary difference between bakelite and glass, this same property would be shown.

Finally, Mr. Connolly said there appeared to be in existence—it might be a trade secret—a synthetic material which by rough physical tests appeared to be better even unreinforced than any of the materials they had been told about by the author. He was referring to a fountain pen cylinder which he had, with a wall of one thirty-second to one-sixteenth of an inch thick and a diameter of one half-inch, and said that as a demonstration point the salesman would stand on that on the floor. Hence the stress must be of the order of 27,000lbs. per square inch, which had been mentioned. If it were possible to find out what that material was—it was obviously a plastic—he thought a very useful material should be available, if the cost were not too high. This seemed to be a working stress rather than an ultimate figure. The toughness was evident, and seemed to be an important quality in aeroplane construction.

Mr. Heywood: With reference to the possibility of using steel or other metal reinforcement in this new material, some time ago he made some simple calculations on the effect of incorporating in the resin a high tensile steel wire. Speaking from memory, he believed he found that 1 per cent. of cross-sectional area in the form of such a steel wire would increase the weight by about 6 per cent. and the effective Young's Modulus by 30 per cent. The effect of the higher Young's Modulus was to put up the tensile strength by about the same amount, assuming the wire to have a tensile strength of about 100 tons per square inch. A very important point, however, came out of that simple calculation. It appeared that the optimum results would be attained by using reinforcement having approximately the same ratio between ultimate strength and Young's Modulus as in the case of the resin. If cotton, hemp or other materials having a high tensile and a fairly low Young's Modulus were used, it seemed to him that long before the ultimate strength of the fibre was reached the resin would have failed in tension, so that actually the strength of the combined material was not given by the resin plus the fibre, but by the fibre alone. The simple experiment which the author had shown them that evening illustrated that point very well. If he were correct, that point was of some importance, because engineers not only wanted to know the ultimate tensile strength of the material, but also the limit of proportionality. Was it correct to say that aerolite had in effect no limit of proportionality and that, if so, it would be unsafe to use the material under repeated stressing much in excess of the ultimate strength of the resin?

Another point was that in the case of metals it was possible to rely on the physical and mechanical properties within a very small percentage of their stated values. Could the author say whether aerolite, using a given resin, could be very closely standardised from this point of view?

Mr. ROBERTS: With reference to the reinforcement of resins by steel bars and the suggestion by one speaker that possibly the adhesion between the two would not be sufficient for that reinforcement to be worth while, he asked whether the author considered it would be possible by simply roughening the surface of the steel bars or drilling small holes in them, to make the two materials combine more satisfactorily, and make them suitable for use in the manufacture of the moulded product, or would the differences in expansion of the materials under heat make that form of construction impracticable, by shearing off the resin "keys" so formed, when cooling from the moulding temperature.

Mr. H. M. YEATMAN (*Associate Fellow*): Has any research work on similar lines been done with respect to urea formaldehyde resins, for instance, when used as an adhesive; or has the unfortunate affinity of urea formaldehyde for cellulose led the author to dismiss it altogether for his purposes?

Major MACLEAN: While the author had referred very considerably to the introduction of reinforcing materials into the resins, he would very much like to know what was known of reversing the process and introducing the resins into existing materials such as wood.

Mr. E. P. KING (*Associate Fellow*, de Havilland Aircraft Company) (*communicated*): There are several very interesting points arising out of Dr. de Bruyne's excellent paper which seem to call for comment in order that the present position and future possibilities of plastic materials may be clearly in the minds of aircraft designers. The lecturer had given them a most stimulating and useful contribution to the available knowledge of the properties of plastic materials and the following remarks are made from the viewpoint of the designer seeking to apply the new class of synthetic materials to aircraft construction rather than the scientist looking at the structure of the molecule.

In the phenolic class of synthetic resinoids—at present the most useful—it is necessary to distinguish between reinforced resins and resin impregnated products. During the course of the discussion following the lecture, Major Maclean asked for some particulars in regard to the relative merits of these types of material. No doubt, therefore Table A following, will be of interest in helping to decide which type should be used in any particular application. It should be noted that the modulus of rupture and values of "*E*" were obtained from tests on small square sectional beams and that the fabric and cord filled material weighed 85lbs./ft.^{3}, whereas the impregnated wood was of lower density and weighed between 70 and 75lbs./ft.^{3}. All strengths are given in lbs./in.^{2}.

TABLE A.

	Tensile strength.	Compressive strength.	Modulus of rupture.	Young's Modulus.	Shear along lams.	Strength across lams.
Standard grade fabric material	10,500	26,000	25,000	1.4×10^6	5,900	7,500
Cord grade material ...	26,000	25,000	30,000	2.8×10^6	5,900	6,900
Impregnated wood (mean for birch, beech and acacia)	20,000	22,000	40,000	4.0×10^6	2,000	2,500

These figures confirm the conclusions given by the lecturer, *i.e.*, that the strength and elasticity of resinoid products depend entirely on the type of reinforcing material placed in the resin—or into which the resin is impregnated. From a comparison of Figs. 6 and 11, however, the conclusion is drawn that, in compression, this dependence is much less marked except in regard to type of failure (c.f. Figs. 8 and 13). After reading Dr. de Bruyne's paper the writer was of the opinion that the rather disappointing elasticity results given in Figs. 6 and 7, 11 and 12 should be taken with some reserve. Accordingly, some independent tests have been carried out, in compression, with standard grade cord

filled material, and with Permali 523 H—a resin-impregnated laminated beech wood. Fig. 1 gives the results of these tests, which, taken in conjunction with those in Table A clearly indicate that for main structural members—where high

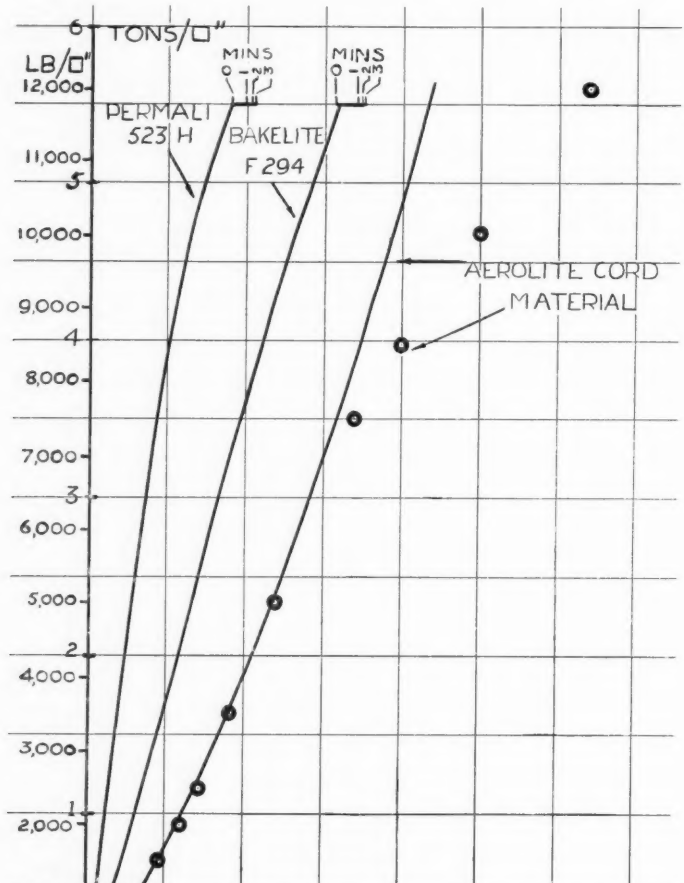

FIG. 1.

elastic modulus is essential—even at the expense of lower shear strength—the resin filled, laminated, natural wood fibre material is much to be preferred.

It often happens, however, that great ultimate strength is not required on the more lightly loaded parts of aircraft structures. What is wanted is a light material, which is self-stabilised over large areas and capable of taking moderate

loads without premature waving. It is interesting to hear that preliminary experiments are successful in this direction. It may be remarked, here, that the writer, approaching from a different angle, has produced a light composite " sandwich " material by " welding " special resin, sprayed facings to a central low density core which acts almost entirely as a means of support and so enables the skin to develop loads approximating to the ultimate strength of the material employed.

It should be clearly borne in mind that in plastic materials a range of mechanical properties is available quite as great as is to be found in the metals ordinarily employed. It is not surprising, therefore, that with so much versatility in characteristics and method of manufacture, it should be essential for the designer to state precisely his particular requirements regarding ultimate strengths in tension, compression, shear or impact, and the importance attaching to high elastic modulus. As has been remarked for most structural purposes great ultimate strength is not in itself the great desiradum unless accompanied by a proportionate increase in elastic modulus. Cord reinforcement gives the strongest mouldable plastic material, but for such applications as spar flanges, struts, etc., lightly impregnated and compressed laminated wood fibre material would seem to give the best results. This material is very water resistant, is easily cemented and may be constructed in long lengths from smaller pieces. Broadly speaking, however, where high stress concentration occurs, mainly along one axis, as in short struts, etc., the high shear, shock absorbing and mouldable properties of cord grade material gives it definite advantages, despite the rather poor position in Table X of Dr. de Bruyne's paper. Incidentally, the stress-strain curve, Fig. 14, shows a modulus approximating to 3×10^6 lbs./ins.^{2} at .02 strain, whereas, 2×10^6 lbs./ins.^{2} is given in the table. The stress-strain curve for plastic materials is very dependent on the rate at which the load is applied and differences of the order given may be expected to be carried out from experiments with different apparatus and rates of loading.

In many applications, as for beams, " long " struts, airscrews, etc., maximum strength is required longitudinally even at the expense of some transverse strength. There are other applications such as for shear webs, gear wheels, pulleys, bushes, cowlings, instrument panels, loading pads, etc., where nearly equal (even if lower) tensile strength is required in all directions, but where great shear strength and freedom from splitting is required. In these cases fine cambric or Egyptian cotton " square " weave filler has been found most satisfactory. Dr. de Bruyne's development of special 45 degrees " aerolite " for shear webs is very interesting, but one would have preferred to see the results shown in Fig. 31 plotted for equal weight and different thicknesses of web. It is suspected that the lower density and greater thickness of the plywood would give this material a definite advantage —at least in the pre-waving stress stage. It should be borne in mind that the behaviour of materials in compression is our chief concern in the design of nearly all structural members and a diminution in modulus may be allowed in cases where the bulk factor is high, or may be made virtually high, by " crinkling," etc.

In the quest for the strongest and stiffest reinforcement, Table II serves as a useful guide, although no information is available in most cases as to suitability for impregnation. Some of the fibres enumerated certainly give very high strength values, but probably it would be impossible to obtain many of them in suitably woven form. Raffia, esparto grass, bamboo, pure silk and rayon have been tried, but for various reasons these experiments have not been very successful. Egyptian cotton fibre de-twisted, suitably woven, and pre-tensioned into the resin gives the best results so far

Several speakers, during the discussion, raised the question as to the possibility of reinforcement by steel or other metal wire. A little reflection will show that the division of loads in such as composite material is not structurally economical, even supposing real adhesion could be obtained between the materials to prevent

slippage. Consider the simple case of a short resinoid strut reinforced with steel wires and compressed between end plates. In this example the load is supposed to be applied evenly to the ends of the specimen so that the tendency to relative axial movement may be neglected. Now since the elastic modulus of steel is approximately 20 times that for the resin, it is obvious that the stress in the steel will be correspondingly greater than that in the resin. The main function of the resin would be to stabilise the slender steel reinforcing wires so enabling them to live up to a higher stress. Thus the contribution of the resin to strength would be 1/20th that for the steel, while its weight would be $\frac{1}{6}$th. Perhaps this will be clearer, if each steel wire be considered surrounded by a sectional area of supporting resin 20 times that for the wire. Accordingly, the load which this will carry will be equal to that taken by the wire, but its weight will be $3\frac{1}{3}$rd times as great.

The proposal to use wire reinforcement near the top and bottom surfaces of beam members certainly deserves very careful consideration, since it has been shown that the low modulus, and consequently high deflection, of resinoid corded fabrics leaves much to be desired in the present stage of development. An analogy is to be found in the use of steel reinforcement for concrete beams, but in this case it is necessary on account of exceptional weakness of the concrete in tension. In the proposed application to resinoid materials the object is to increase stiffness rather than strength, which has been shown to be adequate. Suppose, now, the designer is disposed to allow some additional weight, in order to attain greater beam stiffness, the twin problems of slip and unequal expansion still remain to be solved. As regards the first of these, much depends on the size of wire and rate at which the load builds up in the reinforcement by shear transference from the surrounding mass of resin—that is, it depends on the slope of the B.M. curve. Other things being equal, greater strength would be obtained by the use of a large number of very thin reinforcing filaments rather than by using a few thick ones; for obviously the surface cross-sectional area ratio would be greater and consequently a better shear linkage would be attained. The loosening of the bond between the resin and reinforcement, on account of unequal expansion, is a matter requiring some consideration. The coefficient of lineal expansion of synthetic resin is approximately four times that for steel, but supposing the former "shrunk" on to the reinforcement, this difference of expansion may not be serious over the small temperature range which is likely to occur in practice.

The method of expressing relative strength results in terms of stress and density, as in Table II, is not generally recommended, as it requires very delicate research conditions and is not suited to ordinary laboratory routine. In the Table B which follows, the strength/weight values are given in the manner suggested by Mr. C. C. Walker. This eliminates the necessity for accurate measurement of sectional areas of fabrics and delicate fibres. The strength of a specimen 12in. long, of any sectional area, is given simply as the maximum number of times its own weight which can be supported before failure. This method of expression may be used equally as well for comparing the compression buckling-strength/weight ratios of the various new products now being developed.

Some time ago a need was felt for a means of determining quickly the elastic properties of small experimental samples of resin bonded material. Accordingly a simple apparatus was devised, as shown in Fig. 2, where the cantilever stiffness test is being carried out; the actual deflection under the load being magnified 65 times by means of a long fibre pointer. The elastic modulus obtained by the usual formula is not the true value, but rather lower, on account of the included shear deflection, by an amount dependent on the type of reinforcement used. The "apparent" E, so derived, is nevertheless a very useful quantity, for it represents the relative stiffness of materials under normal beam load conditions. By turning the specimen cross-wise and applying two loads at the extremities of the beam, the shear deflection is eliminated over the central portion, and a very

close approximate to the true elastic modulus is obtained. Table C gives some recent results on relative stiffness of representative materials tested as in Fig. 2.

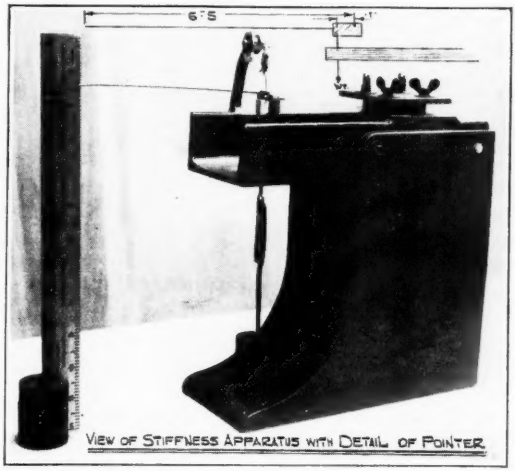

FIG. 2.

TABLE B.

STRENGTH AT RATIOS FOR VARIOUS MATERIALS.

Material and Specification.	Ultimate Tensile Strength of Specimen (lbs. on 12in. specimen).	Weight per 12in. length (lbs.).	Strength/Weight.	Remarks.
Spruce DTD 36 A ...	18,000	0.17	106,000	
	5,000 Compression if stabilised.	0.17	29,400	
Spruce (built up) ...	11,500	0.35	33,000	Resin sprayed and laminated.
	11,200 Compression if stabilised.	0.35	32,000	
Birch (built up) ...	19,600	0.43	45,500	
	10,000 Compression if stabilised.	0.43	23,200	
Balsawood	600	0.055	11,000	
Ozonote	90	0.035	2,600	
Bamboo	40,000	0.49	82,000	
Steel (60 T)	135,000	3.36	40,000	
Steel (80 T)	180,000	3.36	53,500	
Dural (DTD 147) ...	50,000	1.24	40,000	
Electron (88a) ...	33,800	0.78	43,000	
Electron (AZ 855) ...	48,000	0.78	61,000	
Bakelite (F 294) ...	10,500	0.61	17,200	Standard grade.
Bakelite (F 5372) ...	26,000	0.61	42,800	Cord grade.
Linen fabric (5 Fi) ...	90	0.0023	39,000	Min. spec'n. requirements.
Cotton fabric (4 F 8)	80	0.0026	30,500	
Egyptian cotton ...	68	0.00115	59,000	Special weave fabric.
Acetate fabric ...	54	0.00077	70,000	"Square" weave fabric.
Pure silk fabric ...	54	0.00085	62,000	

TABLE C.

RELATIVE STIFFNESS OF VARIOUS MATERIALS.

Material.	Apparent Modulus "E" 10^6 lbs./in.^{2} units.
Steel	27.0
Spruce	1.4
Duralumin	9.0
Electron	6.0
Bakelised veneers	2.9
Permali, edgewise	2.8
,, flatwise	2.7
Bakelite F 294	1.4
,, F 5376	1.7
,, F 5372	2.5
,, urea type paper filled material ...	1.5
Rayon cord material	2.0
,, "square" weave material	1.4
Pure silk material	2.2
Perspex	0.37

Mr. C. C. WALKER (*Fellow*, de Havilland Aircraft Company) (*communicated*): In one part of his paper Dr. de Bruyne says:—"A decrease of density even though accompanied by a decrease in Young's Modulus would be beneficial."

While this is true of a rectangular solid strut or a plain circular cylinder, there is no reason when thinking of aircraft structures to tie themselves down to a particular section. When using metals it is out of the question to avoid the use of reinforcement or convolutions in a skin structure in order to develop a reasonable percentage of the ultimate crushing strength of the material.

If, then, one accepts the fact that whatever material is used, the section will be made stiff enough to avoid secondary failure, one comes back to a more fundamental criterion, namely, the ratio of the Young's Modulus to the strength. Any material which is deficient in this respect will permit undesirably large deflections in the complete structure.

He thought it was better to look at it in this way because it brought out the fact that an improvement in the ratio is necessary before these plastic materials can be considered as being on a par with steel, dural, or spruce. It is, of course, of very great advantage to be able to avoid convolutions and reinforcements of the section by using low density materials, but they could not use a material at all in the main structure if it is deficient in the ratio of stiffness to strength.

If they thought of a short strut made of "aerolite" in the form of a honeycomb of long tubes so that its average density is the same as that of a spruce strut of the same dimensions, the two struts will sustain roughly the same load. Similar struts of steel or dural suitably protected against secondary failure will also sustain about the same load and all will be of the same weight. At the point of failure, however, the aerolite strut will have suffered a compression two or three times as great as the others. For this reason one looks on the spongy light material more as a means of stabilising a relatively stiff skin against secondary failure than as participating fully in the direct stress.

It is, therefore, of great importance that research should be directed towards an improvement in the stiffness strength ratio either by an increase of "E" or a reduction of density and strength at the same "E." Since the physical properties of these materials depend to a considerable extent on the nature of the filler this is not a hopeless quest. The fibres of wood seem to be well arranged for taking stress without too great strain, and it has been found possible to impregnate and compress wood so that its strength and stiffness both increase together, and it retains its status as a structural material.

No other laminated plastic reaches this standard at present, and it is hardly surprising while they continued to use twisted threads to take compression instead of straight fibres.

It may be well to emphasise these points by saying that the ideal structural material would have the strength, density and stiffness of spruce without its capacity to absorb and give out moisture.

This is only looking at the subject from one angle. The value of these materials in other directions is, of course, very great as Dr. de Bruyne has indicated. The combination of low notch-sensitivity and great power of damping and absorbing vibration, with high strength/weight ratio, good bearing qualities, incorrodibility and freedom from moisture effect will compel their extensive use.

Dr. de Bruyne has produced a remarkable paper and has done a great service by keeping research and technics closely related in the important work he is carrying out.

Reply to the Discussion.

Before attempting to answer some of the questions raised, I should like to thank all those who have taken part in the discussion for their help in clearing up some obscurities and emphasising points of interest. Several speakers have asked why metal reinforcement is not used since although the ultimate strength of the resulting material might not be greater than with cellulose reinforcement, the stiffness should be considerably improved. Messrs. Heywood, King, and Philippe have given convincing reasons why metal, though superficially attractive, is not really a helpful solution to the problem. I have nothing to add to their remarks except to point out that in addition there is a good reason (mentioned by Mr. C. C. Walker in a recent conversation) for avoiding if possible the use of metal reinforcement on the grounds that the use of metal would introduce into the material all those poor fatigue and energy absorbing qualities associated with matter in a crystalline form.

I am afraid that my use of the word " aerolite " to distinguish reinforced phenol formaldehyde from the pure resin (which I have called " bakelite ") has caused some confusion, but if it will be borne in mind that the words are used with just the significance stated and no more, I believe no confusion need arise. Dr. Lanchester has pointed out that in " Astra Castra " the word is used for a meteorite; it may well be that I have been guilty of a kind of subconscious plagiarism as I also have a copy of that remarkable book, though I have not read it for many years.

The word " syneresis " means a spontaneous contraction in a gel accompanied by a squeezing out of the liquid in its pores.

Stäger's results given in Fig. 26 show the actual tensile force required to pull apart two metal surfaces cemented together with the various resins stated. They are of interest as they show the variation in the number of adhesive bonds during polymerisation, but they must not be taken to mean that joints made with bakelite cement will decrease in strength with time since the results refer to the use of bakelite initially in a low state of condensation.

The curves in Fig. 28 have been spread out along the x axis by arbitrary amounts for the sake of clearness. No observations were made at stresses less than 5,000lbs./sq. in. because play in the apparatus gave anomalous readings at stresses below this figure.

It is too early to say with confidence what degree of consistency may be obtained in the properties of aerolite in production, but I do not myself see why there should be any difficulty in meeting the minimum requirements of a specification, just as, for instance, casein cement is required to meet the requirements of B.S. specification 3 V 2.

The tensile strength computed from beam tests is higher than that obtained in a tensile test because, as already pointed out, the neutral axis continually moves towards the compression side of a beam as the bending moment is increased.

I do not think that the analogy with concrete should be pushed too far. In aerolite the resin is moulded under high pressure and all the evidence points to it being left in a state of initial compression so that there is far less liability for the formation of hair cracks. Moreover, the reinforcement in aerolite is far more extensive and more uniformly distributed than the reinforcement in concrete, so that the resulting material has qualities different from those of its constituents. Lastly, the presence of free phenol in aerolite guarantees that no attack by fungus can take place; this is exemplified by the fungus resisting qualities of plywood bonded with phenol formaldehyde resin in comparison with plywood stuck together with casein albumen or gelatine glue.

I understand from Mr. Dunton's remarks that he has developed materials with high impact values as measured by a modified Izod test. A high Izod figure does not mean of course a high " energy absorption " in the sense in which the words have been used in the lecture nor is it related to the ability of a material to withstand repeated impact (as measured, for instance, in an Amsler repeated impact machine). My own view is that the physical significance of the Izod test is so obscure that it is better to neglect it in describing the strength characteristics of materials, but that the test may be an extremely useful one in controlling and supervising the quality of a material in production as any deviation from a standard is thereby made evident.

We have done a certain amount of work on urea formaldehyde reinforced resins and believe the brittleness difficulty can be overcome, but even then the material is heavier and probably less weather resistant than phenol formaldehyde resins.

Mr. King has made a valuable contribution and has replied to Major Maclean's enquiry more fully than I could have done. The stress-strain curves in the lecture are not examples of the best that can be achieved, but are given chiefly to illustrate the form of the relations.

I entirely agree with Mr. Walker that we have not yet reached the stage where aerolite is a direct competitor with existing materials except in particular applications such as where a high bearing strength is required. However, as the result of work carried out since the delivery of the lecture above, we have been able to increase the value of E for aerolite (without metal reinforcement) to 5.9×10^6lbs./sq. in., so that I feel confident that we can produce a satisfactory material in time.

On the motion of the President a cordial vote of thanks was passed to the author at the conclusion of the discussion.

AN ANALYSIS OF THE FLIGHT OF AN AEROPLANE, WHEN DIRECTED BY MEANS OF A RADIO BEACON, FOR ALL POSSIBLE VALUES OF WIND VELOCITY.

By F. B. Greatrex, B.A.

In these days of long distance flights across large stretches of ocean aeroplanes will make considerable use of radio direction-finding apparatus, enabling them to keep their course on to a transmitting station at their goal. Over the Atlantic, for example, a series of beacons all the way across would be quite impracticable. The following is an analysis of the course flown by an aeroplane under these circumstances, showing also the increase in flying time over that on a compass course, and also the maximum deviation from the compass course.

Symbols Used.

a = great circle distance between start A and finish O of flight.
v = air speed of aeroplane.
u = wind speed.
$n = v/u$.
α = angle between wind direction and the perpendicular to AO (positive when "above" Ox, negative when "below").

All calculations are made for different values of n and α. The range from $n=2$ to $n=7$ covers all the conditions likely to be met in practice. α is varied from $-90°$ to $+90°$.

Equation of the Flight Curve.

Fig. 1 shows a much exaggerated curve of the type under consideration.

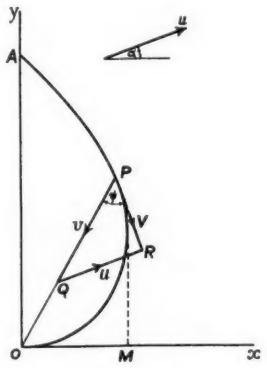

FIG. I.

At any point P, on the curve, the triangle of velocities is PQR. PQ represents the air speed (v) of the aeroplane (always directed towards O). QR represents the wind speed (u).

PR, the resultant of these two, represents V, the ground speed along the curve.

Using polar co-ordinates $OP=r$, and $POx=\theta$. In the triangle PQR, we have $PQR=\theta-\alpha$. Let $QPR=\psi$. Then

$$u/\sin\psi = v/\{\sin(\psi+\theta-\alpha)\}.$$

$$\therefore\ n=v/u=\cos(\theta-\alpha)+\cot\psi.\ \sin(\theta-\alpha).$$

But $\tan\psi = r(d\theta/dr)$.

$$\therefore\ n\ \mathrm{cosec}\,(\theta-\alpha)-\cot(\theta-\alpha)=(1/r)(dr/d\theta).$$

Hence, integrating,

$$r = A\ \mathrm{cosec}\,(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^n \quad . \quad . \quad . \quad . \quad \text{(i)}$$

the equation of the curve

In it A is a constant defined by the fact that when $\theta=90^\circ$, $r=a$. This gives

$$A = a\cos\alpha\{\cot\tfrac{1}{2}(90^\circ-\alpha)\}^n \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

Figs. 2, 3 and 4 are examples of this curve, showing how it is affected by changes in n and α.

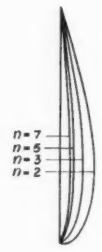

FIG. 2.

FLIGHT CURVES FOR $\alpha=-30^\circ$

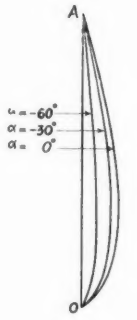

FIG. 3.

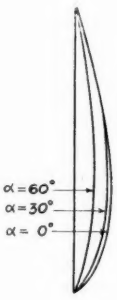

FIG. 4.

FLIGHT CURVES FOR $v/u=3$

It is interesting to note here that at O, when $r=O$,

$$\tan\tfrac{1}{2}(\theta-\alpha)=0.$$

$$\therefore\ \theta=\alpha,$$

i.e., an aeroplane guided by a beacon on its terminal aerodrome will always arrive at the aerodrome against the wind, *i.e.*, in the right direction for landing.

TIME OF FLIGHT.

The equation of the curve is

$$r = A\ \mathrm{cosec}\,(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^{v/u} \quad . \quad . \quad . \quad \text{(iii)}$$

$$\therefore\ dr/d\theta = A\ \mathrm{cosec}\,(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^{v/u}[(v/u)\ \mathrm{cosec}\,(\theta-\alpha)-\cot(\theta-\alpha)] \quad \text{(iv)}$$

To find the length (s) of the curved path, we have

$$(ds/d\theta)^2 = r^2+(dr/d\theta)^2.$$

Substituting from (iii) and (iv) this gives

$$ds/d\theta = (A/u)\ \mathrm{cosec}^2(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^{v/u}[u^2+v^2-2uv\cos(\theta-\alpha)]^{\frac{1}{2}} \quad \text{(v)}$$

But from Fig. 1 it can be seen that $V^2=u^2+v^2-2uv\cos(\theta-\alpha)$ and to find the time of flight we have $dt=ds/V$.

Substituting these in (v), we get

$$dt/d\theta = (A/u)\ \mathrm{cosec}^2(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^{v/u}.$$

$$\therefore\ \text{Time of flight} = T = (A/u)\int_{\alpha}^{90^\circ}\mathrm{cosec}^2(\theta-\alpha)\{\tan\tfrac{1}{2}(\theta-\alpha)\}^{v/u}\,d\theta.$$

This finally gives us, after substituting for A from (ii),

$$T = \{ a/(v^2 - u^2) \} (v + u \sin \alpha) \quad . \quad . \quad . \quad . \quad . \quad (vi)$$

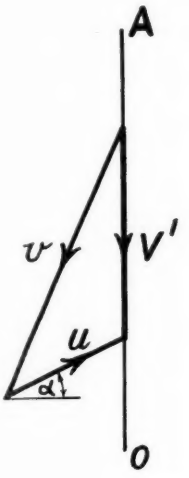

FIG. 5.

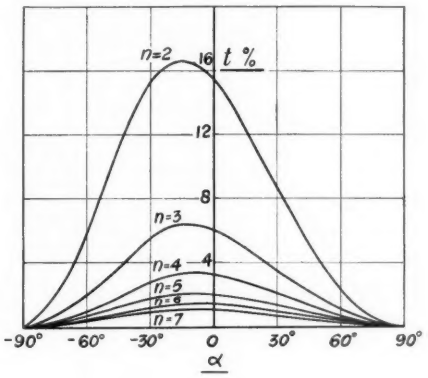

FIG. 6.

For an aeroplane flying on a straight line course between the two points, the triangle of velocities is as shown in Fig. 5. The ground velocity V' is constant, and given by

$$V' = \sqrt{(v^2 - u^2 \cos^2 \alpha)} - u \sin \alpha$$

and time of flight $= T' = a/V'$.

$$\therefore \quad T' = \{ a/(v^2 - u^2) \} \ \{ \sqrt{(v^2 - u^2 \cos^2 \alpha)} + u \sin \alpha \}$$

which may be compared with (vi).

The useful figure here is $t = 100 \{ (T - T')/T' \}$, *i.e.*, the percentage increase in flying time on the curved course over that on the straight line course.

Table I shows the variation of t with n and α, and the results are plotted in Fig. 6.

TABLE I.

To plot the curve for $n = 2$, an additional value $\alpha = -15°$ is needed, giving $t = 16.60$ per cent.

	t % when α (in degrees) =						
n	−90	−60	−30	0	30	60	90
2	0	5.98	15.23	15.47	8.60	2.29	0
3	0	2.01	5.44	6.05	3.83	1.10	0
4	0	1.00	2.82	3.31	2.18	0.65	0
5	0	0.61	1.70	2.04	1.38	0.43	0
6	0	0.41	1.16	1.42	0.97	0.30	0
7	0	0.30	0.84	1.04	0.72	0.21	0

MAXIMUM DEVIATION FROM STRAIGHT LINE COURSE.

On some routes a deviation from the straight line course might take the aeroplane over a militarised zone, or into a mountain range. Consequently this maximum deviation (OM in Fig. 1) is a useful quantity to know.

Multiplying (i) by $\cos\theta$, we have

$$x = r\cos\theta = A\cos\theta\,\operatorname{cosec}(\theta-\alpha)\,\{\tan\tfrac{1}{2}(\theta-\alpha)\}^n \quad . \quad . \quad \text{(vii)}$$

$$\therefore\ dx/d\theta = A\operatorname{cosec}(\theta-\alpha)\,\{\tan\tfrac{1}{2}(\theta-\alpha)\}^n\,[\cos\theta\,\{n\operatorname{cosec}(\theta-\alpha) - \cot(\theta-\alpha)\} - \sin\theta].$$

Putting $dx/d\theta = O$, to find x_{max}, we get

$$\cos\theta\,\{n\operatorname{cosec}(\theta-\alpha) - \cot(\theta-\alpha)\} - \sin\theta = 0.$$

$$\therefore\ \cos\theta = (1/n)\cos\alpha.$$

Substituting this in (vii) gives x_{max}, shown in Table II, as a percentage of $AO\ (=a)$.

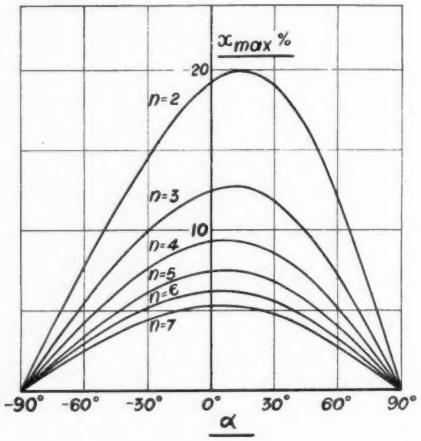

FIG. 7.

Fig. 7 shows x_{max} plotted against α for different values of n.

TABLE II.

	x_{max} % when α (in degrees) =						
n	−90	−60	−30	0	30	60	90
2	0	7.66	14.57	19.24	19.01	12.06	0
3	0	5.52	9.93	12.50	11.78	7.24	0
4	0	4.18	7.55	9.28	8.57	5.19	0
5	0	3.40	6.07	7.41	6.72	4.04	0
6	0	2.86	5.08	6.16	5.57	3.29	0
7	0	2.48	4.40	5.25	4.73	2.81	0

APPENDIX.

It may be interesting to give one particular example of the use of these results. Consider the flight from England to America and back, assuming the distance $(a) = 3{,}000$ miles; a south-west wind of 30 m.p.h. making $u = 30$ m.p.h., $\alpha = \pm 60°$ approx. (since London and New York are not at the same latitude); an air speed (v) of 210 m.p.h. for the aeroplane, making $n = 7$.

Substituting these values in (vi) we get for the times of flight

Outward ... = 16 hrs. 20 mins.

Return ... = 12 hrs. 45 mins.

From Fig. 6 it can be seen that the increase in time over the straight line course = 0.2 and 0.3 per cent. respectively, = about 2 minutes in each case, and is therefore quite negligible.

Finally the maximum deviation found from Fig. 7 = 2.8 and 2.5 per cent. respectively.

$\therefore$ maximum (northward) deviation on outward flight = 84 miles.

And on return flight ... ... = 75 miles.

METEOROLOGICAL SUB-COMMITTEE.

AERONAUTICAL RESEARCH COMMITTEE.

THE FORMATION OF ICE ON AIRCRAFT.*

By H. Noth and W. Polte.

Translated by A.I. (T) Air Ministry.

1. General.

The main reasons why trouble due to ice formation on aircraft was not experienced so much in the earlier days of flying as now were two-fold. (*a*) The greatly restricted amount of flying done during the winter and (*b*) the absence of means whereby flight in cloud for any considerable length of time was possible.

The degree to which ice forms, however, differs widely. Since much depends on the relative speed of the aircraft, free balloons are practically excluded. In the worst case ice cannot form on such aircraft to the extent to which heavy glazed frost is observed on the ground, unless the balloon pilot is a very bad navigator and remains in the danger zone longer than would be required for the ground surface to be coated with glazed frost.

2. Processes and Types of Ice Formation.

The meteorological and physical conditions and phenomena associated with ice accretion are extremely complicated and even to-day are imperfectly known.

The most important and most frequent case occurs when flying in cloud at temperatures below 0°C. These clouds are composed of very small water droplets, the temperature of which is also below 0°C., and which are thus super-cooled and accordingly still in the liquid state. Super-cooled water in most cases solidifies at the moment it is disturbed or comes into contact with ice. When an aeroplane or an airship flies through clouds of this nature, both possibilities are nearly always present. Since super-cooled water droplets persist in the liquid state down to −20°C., ice accretion is possible down to this temperature and beyond. This has been proved in practice. The severest and most frequent cases of ice formation are observed between 0° and −6°. The beginning of ice formation is not restricted to the 0° limit. There are processes in which accretion first begins a few degrees above zero and others in which it begins slightly below 0°. These phenomena will be considered later.

When considering the thickness of the ice accretion and the speed at which it forms, the following points should be borne in mind:—

Since the rate of descent of the water drops varies between 0.001 m./s. and, in the extreme case, 7 m./s., according to their size, whereas the speeds of aeroplanes vary between 40 and 100 m./s., the air space through which the aircraft travels during the process of ice formation may be imagined as filled with stationary water drops.

The speed at which the ice forms accordingly depends on the speed of the aeroplane. It forms, for example, in the case of an aeroplane travelling at 100 m./s., twenty times as rapidly as glazed frost on the ground, on which the super-cooled water drops are precipitated vertically at a speed of 5 m./s.

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The thickness of the ice accretion depends (*a*) on the quantity of super-cooled water drops present per cubic metre of air, and (*b*) on the distance travelled by the aeroplane in the ice formation zone or the length of time during which the process takes place, and (*c*) on the particular qualities of the aeroplane.

A further decisive factor with regard to the thickness of the ice formed is the angle at which the drops strike the part of the aeroplane concerned, *e.g.*, the leading edge of the wings. The thickness of the accretion in the case of super-cooled large rain drops may thus be reduced to the formulæ :—

$$E_t = \delta w v t \sin \delta C,$$

where E_t = ice formed per unit area.
δw = water content per unit volume.
v = relative speed of flight.
t = time.
δ = angle of impact.
C = constant.

The question now arises as to the types of ice formation which may be produced. The kind of ice varies according to the preliminary conditions for the accretion; the data at present available with regard to the production, form and colour, are still widely varied or represent transitions from one form to another, so that a description is difficult. The water droplets in suspension may be so minute that they are carried away from the aeroplane with the air stream; no appreciable formation of ice will then occur. Presumably the ice accretion is associated in some way with the boundary layer and the size of the drops. Even at the highest speeds a velocity potential must exist from the surface of the wing to the free air stream. The potential will be the greatest, *i.e.*, the layer of air involved will be thinnest at the positions where the air stream meets the surface at an angle of about 45°. Very small water droplets of 1/1,000 or 1/10,000 mm. diameter will flow past a wing like molecules of air along the boundary layer, which acts like an air cushion, so that contact with the surface, and hence ice formation is prevented. It is only after the drops have reached a definitely determined size that, owing to their inertia, they will be capable at those positions where the angle of incidence is about 45° of penetrating through the boundary layer and attaching themselves to the surface. As the drops increase in size they may become able, even in the dead water zone, that is when approaching at angles of 45° to 90°, to penetrate the thicker boundary layer and cause ice to form directly on the forward side of a body washed by the air stream. In practice it has frequently been observed that with light ice accretion the latter begins at a certain distance from the leading edge of the wing.

The various forms of ice accretion may be divided roughly into three types :—

(*a*) The ice appears as a glassy, almost transparent coating, the surface is relatively smooth. The deformation of the parts of the aeroplane subjected to the ice accretion keeps within moderate limits. This ice is probably produced when an aeroplane flying either in or under the clouds meets only super-cooled water droplets or super-cooled rain. If super-cooled water droplets of varying size simultaneously strike an aeroplane, *e.g.*, when super-cooled rain from a higher cloud layer falls into the lower layer in which the aeroplane is flying, the surface of the ice will become rougher and less uniform. An aeroplane part will become enwrapped and covered in varying measure (up to one-third of its cross-section from the leading edge) according to the speed of descent and size of the drops (Fig. 1). The adhesive capacity of this ice is of a fairly high order, but it may be hammered off with a hard object.

(*b*) The ice is milky in appearance and not very transparent. The surface is rough and frequently exhibits a granular or crystalline-splintery

texture. The accretion on the leading edge generally grows very rapidly, forms a continuously thickening projection which has the peculiarity of growing more rapidly at the side than at the centre, so that the frontal side of the ice forms a relatively wide surface (Fig. 2).

FIG. 1.

The deformation is considerable. This has a marked effect on the aerodynamical qualities and performance of the aeroplane. This ice is probably produced in a cloud by super-cooled water droplets and simultaneous solid precipitation. According to the size and type of the solid precipitation, small, knobbly humps may form on the surface on which the super-cooled water droplets may become more thickly deposited and thus form a peak opposing the air stream. The granular surface together with the tooth-like points formed on it (like those of a circular saw) then imparts the peculiar roughness to the whole accreted ice.

FIG. 2.

This form of accretion grows very rapidly when the temperatures lie in the neighbourhood of 0°. The adhesive capacity is not of a high order since the parts of the aeroplane affected are not so extensively enveloped.

(*c*) A type differing in production, thickness and form, is observed chiefly at temperatures of $-10°$, and more. This accretion is not of the glassy kind, but is of a crystalline snow-like character and settles in relatively small quantities on the leading edges. The deformation is slight. It is more a question of pointed heaps in the dead water region of the parts of the aeroplane affected (Fig. 3). Strange to say, an accretion is found on the airscrew extending from the hub almost to the blade tip. The adhesive capacity is of a high order. The ice cannot be hacked off without causing damage and must, therefore, be thawed off.

FIG. 3.

Besides the cases described above, with which the aeroplane pilot is most frequently concerned, there is another kind of deposit of snow or hoar frost.

For example: An aeroplane is flying in or below the clouds in a layer of air at a small positive temperature. If thick flaked snow now falls (it is known that a snow flake can fall about 100 metres in a layer of a temperature above 0° without completely melting), this slushy snow will settle firmly on the leading edges. A continuous settling and simultaneous melting down is now observed. It will depend on the temperature and conditions of humidity in the zone in which the aeroplane is travelling, whether the deposit increases or not. Owing to the

cold due to evaporation the temperature at the leading edge may at any time drop so far that the deposit will freeze and then grow thicker.

3. Special Cases.

A further very rare case occurs when *at a high altitude* in the "ice needle clouds" or even in the cloudless space, a light *accretion of hoar frost* of hardly measurable thickness forms on the aeroplane. It is caused either by the aeroplane becoming intensely cooled in the cold layers and then suddenly entering somewhat warmer and more humid air masses where it becomes coated with moisture rather like glasses, when going from a cold into a warm room. The hoar frost may also be produced as the result of super-saturation of ice on an aeroplane coated quite thinly with ice. Again, transparent air but nearly saturated with water vapour, precipitates ice or frost on ice, whilst it gives out none of its moisture content as yet where water or a dry aeroplane are concerned.

Dr. Reidat, the leading meteorologist at the Berlin Meteorological Station, where twice daily scientific aerological research flights to altitudes of 5,000 to 6,000 metres are carried out, reports on the following observation: "It is frequently observed when flying in cloud that super-cooled water drops do not immediately freeze on striking the aeroplane. The super-cooled water first forms a film of liquid which trickles away in drops (the temperatures of both water and aeroplane are definitely below 0°). The super-cooled water, however, freezes almost regularly when the aeroplane reaches the cloud surface and the blue sky becomes visible above. When climbing, the aeroplane at first is slightly warmer or at any rate of the same temperature as the air. The drops do not become further cooled when coming into contact. As the drops coalesce, the water surface is reduced, the surface tension decreases; no energy is withdrawn from the drop, some is imparted to it. In most cases at the upper boundary of the cloud there is marked decrease in the relative humidity. Consequently rapid evaporation with cooling takes place, the water present on the wings, etc., immediately freezes even that which has found its way aft to the tail surfaces. When descending and re-entering the cloud, the super-cooled droplets immediately freeze on meeting the film of ice now existing on the aeroplane. The accretion of ice then grows rapidly, in regions below 0°, also where previously no ice formation has been observed."

Ice formation at temperatures above 0°C. has definitely been proved in rapid descent; when the aeroplane is always several degrees colder than the surrounding air.

Ice may, however, form in the case of prolonged flight at uniform height where there are temperatures above 0°. An essential condition here is that the air layer is dry and that rain falls into it from above. The evaporation of the film of water on the surface of the aeroplane then causes a drop of temperature of several degrees. The surface of the aeroplane accordingly maintains a negative temperature so long as it is damp, so that any water drops precipitated on it freeze hard. These water drops, owing to their fall and the evaporation in the dry air, are as a rule colder than the latter and in many cases already super-cooled. Ice formations of this kind naturally are to be expected at temperatures only up to about +3°. Since such conditions are not infrequent, cases of ice formation must often have been caused in this way.

These cases are very difficult to prove. Instances of ice formation with positive temperatures have certainly often been reported, but absolute proof has been impossible owing to the difficulty of determining the temperature exactly. It should be pointed out that the thermometer also becomes damp and consequently, owing to the cooling due to evaporation, may indicate too low a temperature, when actually the free atmosphere is considerably warmer.

Further, a case is known, when two aeroplanes flew simultaneously from Stettin to Berlin. In one case there was no trace of ice accretion observed,

whilst in the other, owing to ice accretion, the speed of the machine was reduced nearly to its lower limit and it was just able to land in a completely iced-over state, in Berlin. The aeroplanes were flying close together, but not at exactly the same height.

The cause of this rare phenomenon lies in the peculiarity of the temperature distribution. This is shown diagrammatically in Fig. 4. (The temperature charts corresponding to Fig. 4 may be seen at any time at all meteorological stations.) By way of explanation, it should be noted that the temperature, owing to the intermixing of the lower layers which always occurs with a wind, air is lifted and meanwhile cooled till at a height of several hundred metres (200 m. to 600 m. in winter) it becomes almost regularly colder. In the case in

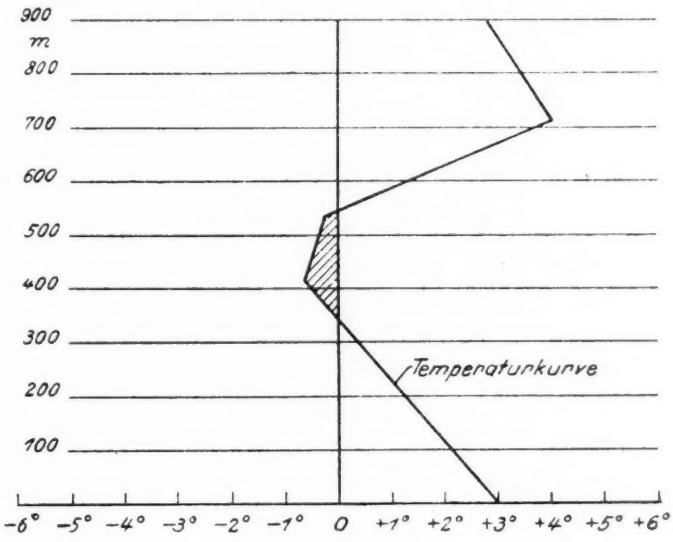


FIG. 4.

question, negative temperatures prevailed from 350 to 450 metres. The general rainfall in this zone was super-cooled and froze on to the aeroplane. The pilot, unfortunately, managed to choose just this height at which he continued the whole flight. Had he flown only a 100 metres higher or lower there would have been just as little ice formed on his machine as on that of his friend, who by luck had avoided the unfavourable air layer.

4. EFFECT OF ICE FORMATION.

In the case of airships, the most obvious effect is the increase in weight. It should be noted that a sheet of ice only 5 mm. in thickness means a load of 5 kg. per sq. m. A load of this order may lead to catastrophe (Nobile's Arctic flight). Fast ascending and descending stratosphere balloons, too, may acquire a thick accretion of ice which as non-jettisonably ballast falsifies any previous calculation of reserve disposable ballast.

The circumstances are quite different in the case of an aeroplane. The ice accretion first comes into evidence on the leading edges of the parts most exposed to the relative wind, such as struts, bracing wires, tail surfaces and wings. The

beginning and the progress of the accretion is best observed on the parts with small profile. The effects on the wing unit, engine, airscrew and instruments are as follows:—

The deformation of the wing has a detrimental effect on the coefficients of drag and of lift, which may increase to such a degree that the aeroplane cannot continue flight even with engines at full throttle.

Ice accretion on or in the aerial shaft has a highly detrimental influence unless means are applied for its prevention. In particular, it will cause a rapid loss

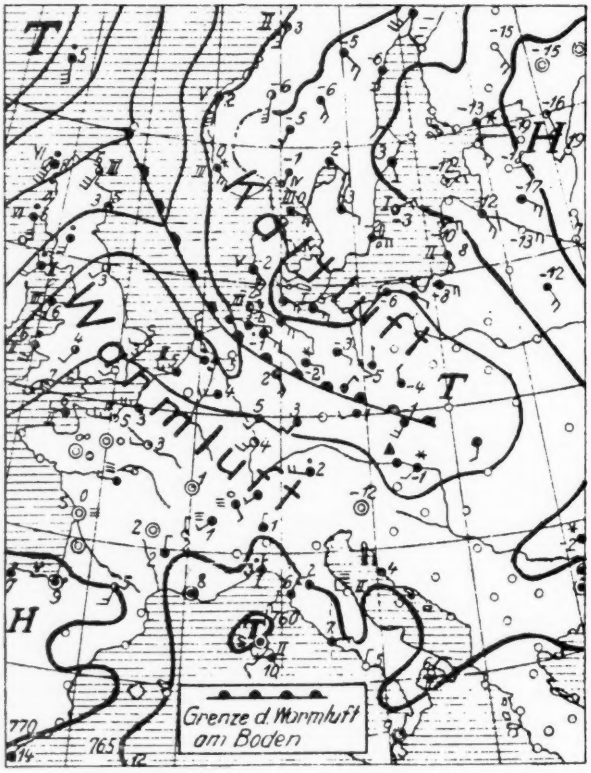


FIG. 5.

of energy which may drop to zero since a connection with mass is produced. Fractures affecting the whole shaft itself are of relatively rare occurrence. All fixed aerials are affected. Aerials fitted transversely very soon begin to oscillate, and are liable to come adrift and get entangled in the tail. Even aerials fitted in the direction of flight require protection to guard against loss. External lighting systems and generators driven by the relative wind are affected in the same manner. Either the screws break off owing to loss of balance or run hot in the bearings. The vibrations and oscillations of the apparatus as a whole

may acquire such large proportions that it may get detached from its foundation and cause damage in flying off.

The material and type of aeroplane matter so far as the beginning of ice accretion is concerned. When once the first film of ice has been formed, progress is equally rapid in nearly all aeroplanes. In the case of monoplanes with a thick profile, ice accretes more slowly than, for example, on biplanes with a thin wing section. Conditions are different in the case of metal aeroplanes from those with fabric covering or with wooden wing unit. The nature of the surface plays a definite part in the initial stage. A seam or line of rivets running along the nose stringer, for example, will promote ice accretion.

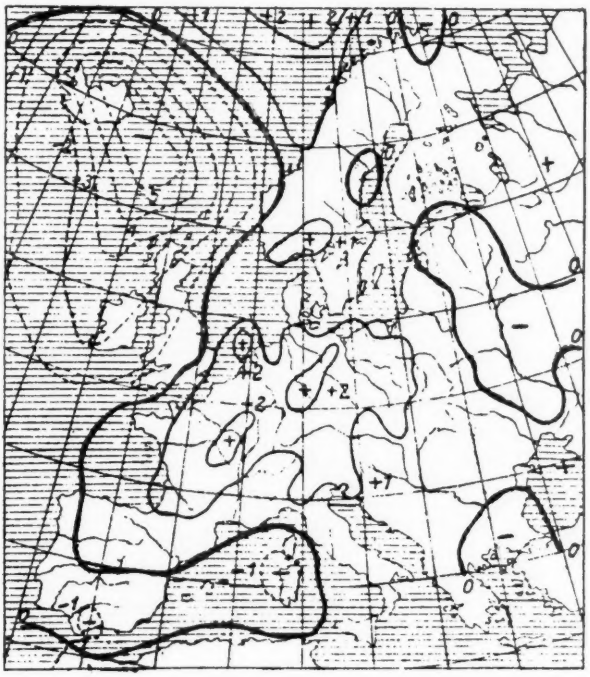


FIG. 6.

A further important question concerns the thickness to which the accretion may grow till it causes trouble. Only a rough idea can be given. A thickness of about 1 to 2 cm. is sufficient to produce perceptible change in the flying qualities and performance. This depends on both the type of aeroplane and the type of ice. The rough surface of a mixture of hard rime and glazed frost has the worse effect. Cases are known in older types of aeroplanes, where the accretion has reached a thickness of more than 5 cm. and on some of the more exposed parts, as much as 10 cm. Under such conditions the aeroplane could no longer continue flight.

Again, the time necessary for the ice to grow to a thickness of some centimetres varies widely, and depends on the relative humidity of the air. Cases are known when, after flying from five to ten minutes, the machine was so covered

that the pilot was obliged to make a forced landing immediately. With low relative humidity, however, flights have been continued in clouds for one to two hours without the accretion becoming more than 2 cm. in thickness.

5. Weather Conditions and Ice Formation.

Ice may form in any weather in any cloud where the temperature is below zero. It forms most rapidly in clouds of the cumulus, strato-cumulus and cumulo-nimbus types. In clouds in which water vapour is still in the process of condensation the formation is intensified. This is the case with all clouds lying above the wedge of cold air or in a mass of air on a warm front. Precipitation from the clouds is not absolutely essential. Figs. 5 and 6 are charts showing weather conditions of this kind. Fig. 7 represents a vertical section through.

The most dangerous case occurs in cold air at a low height, but in different ways. Either warm air flows with great violence to stationary, flat masses of cold air or flat cold air is impelled violently below warm air. An example of the former case is given in Fig. 5. The weather chart indicates a depression over

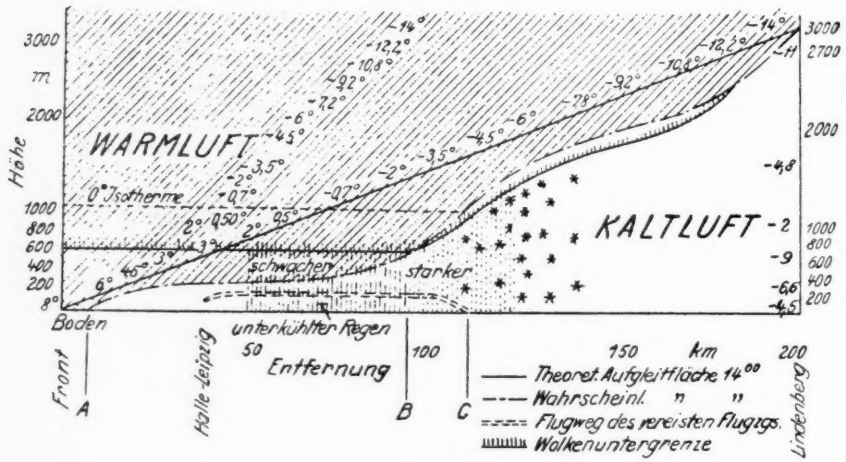
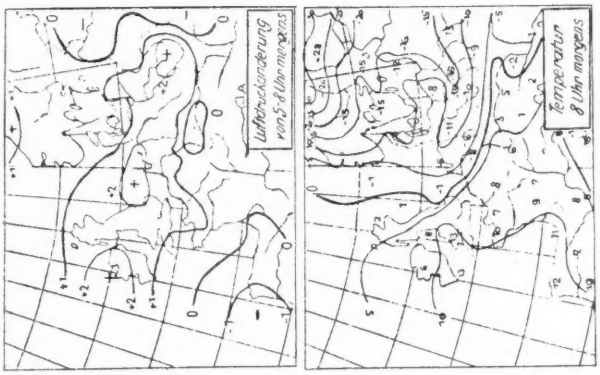


Fig. 7.

Iceland, from which a tongue extends over Holland as far as Bohemia. In the axis of this tongue warm masses of oceanic air from the S.W. meet masses of cold air of Polar-Continental origin. The cold air masses remain at the earth's surface, the warm air masses move away above it.

At the ground there is thus a wedge of cold air rising from about 100 m. to 1,100 m. and containing air below 0° and super-cooled rain. Above this there is air above 0°, though in the warm air above 1,100 m. there are minus temperatures as well (Fig. 7). From the topmost cloud layer snow or rain falls into the warm air, where any snow flakes will thaw. The rain now falls into the lower layer of cold air where temperatures several degrees below zero are found. It becomes super-cooled and the drops which come into contact with the aeroplane immediately settle as ice. Fig. 7 further shows that the frost free air layer projects a long way beyond the cold air in a continuously flattening tongue. By making use of these conditions through meteorological vertical navigation, the



FIGS. 8B AND 8C.

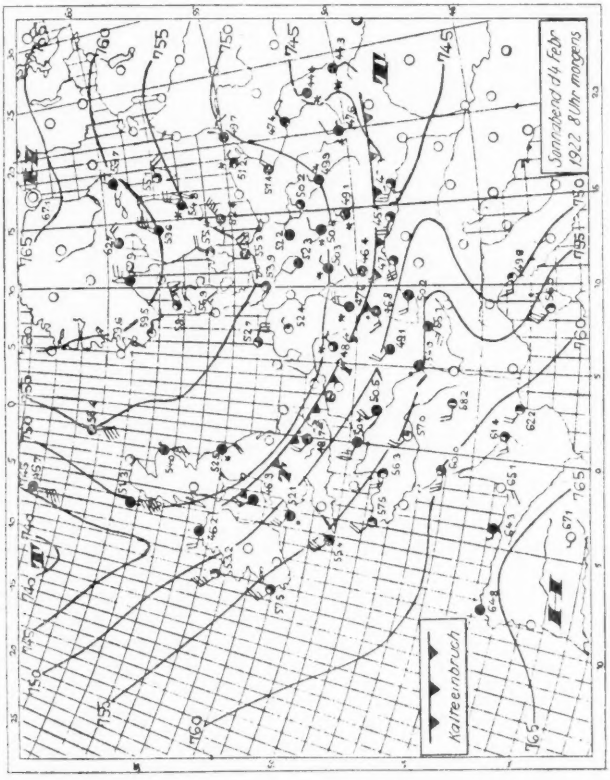


FIG. 8A.

pilot, aided by meteorological advisers, is enabled to ascertain the safe region. Three rules should be observed in this connection:—

(*a*) The weather conditions favourable to ice formation resemble summer thunderstorm conditions. Tongues of low pressure (called in summer "thunderstorm sack") with steep rise of pressure on the western side (Fig. 6). It is the state of weather presented with the change from frost to thaw.

(*b*) The average gradient of the warm front surface is 1 : 200 to 1 : 100, that is, when the warm front at the surface has reached the next point, say at a distance of 100 km. the upper warm air will be at a height of 500 to 1,000 m.

(*c*) Whether the temperatures above the cold air will rise above 0°, depends on the height of separation and the temperature at the ground surface behind the warm front. In the warm air a vertical temperature drop of 0.6°C. per 100 m. may be estimated. If, for example, the temperature in the warm air region rises to 7°C. and the warm air lies at a height of 1,200 metres above the departure aerodrome, the temperature of the warm air here will be $7-(12\times 0.6)=-0.2$°C. This means, however, that the frost free tongue will not extend as far as above this point thus any ice accreted below will not be thawed by climbing higher.

With weather changes in the reverse order, viz., from mild to cold, very severe ice accretions may also be produced through super-cooled rain. Such cases, however, are far more rare. As a rough estimate they occur in about the proportion of 1 : 100. Figs. 8*a*, *b*, *c*, indicate weather conditions of this kind. The change in the weather in this case was extraordinarily abrupt. At Mainz, for instance, at 07.00 hrs. it was raining with a temperature of −8°C. and a strong west wind in currents. At 08.30 hrs. it was raining with an equally strong N.E. wind still in currents and a temperature of −3°C. The rain did not turn into snow until later; in the late afternoon the temperature had already reached −6°C. The intensely super-cooled rain of the forenoon produced a sudden and very severe ice formation on all objects exposed to the weather.

This is again a case of weather which, in summer, would have produced a thunderstorm. The cold air was flowing in at an angle of 1°, which could be determined from the fact that the influx of cold air was observed simultaneously on the Feldberg in the Taunus Mts., and at Darmstadt (40 km. distant). The angle is slightly larger than in an influx of warm air, the gradient at the surface being about 1 : 60.

Flight above the ice producing layer in this case would have been easily possible, but not a take-off or preparation to land within the region of the super-cooled rain, since two to three minutes spent in the extremely heavy rainfall would have been enough to render an aeroplane incapable of remaining in the air.

If snow or rain are falling simultaneously outside the clouds (weather conditions as in Fig. 5), at a temperature below 0°C., this is a sign that the tongue of warm air is still very shallow. It may, however, also be possible that super-cooled water drops falling from above for some reason or other will suddenly solidify; in this case liquid and frozen drops will appear simultaneously. In both cases the frozen precipitation will be caused by the liquid precipitation to freeze on.

Soft rime or an accretion of a soft rime character is observed when flying in clouds at relatively low temperature or even in cloudless, but very humid air. No particularly characteristic state of weather is given, but definite physical conditions must, however, be fulfilled. As a general rule, rime forms when the aeroplane is colder than the surrounding air, a state of affairs which is nearly always presented when making a descent.

6. MEANS FOR THE PREVENTION OF ICE ACCRETION.

(*a*) *Horizontal Navigation.*—The best means of preventing ice accretion is to avoid the zone in which it would be promoted by suitable horizontal or vertical navigation. The most severe accretion generally occurs in elongated zones associated with "fronts," *i.e.*, the boundaries between air massed (*cf.* "Luftwissen," Vol. 2, 1935, No. 6, p. 180). The weather stations provide information on the position of these fronts which are marked on their weather charts. An ice forming front should never be traversed through a long section, but the path should lie at right angles to it, in order to reduce the time of exposure to the danger of ice accretion to a minimum (Fig. 9). This horizontal navigation will

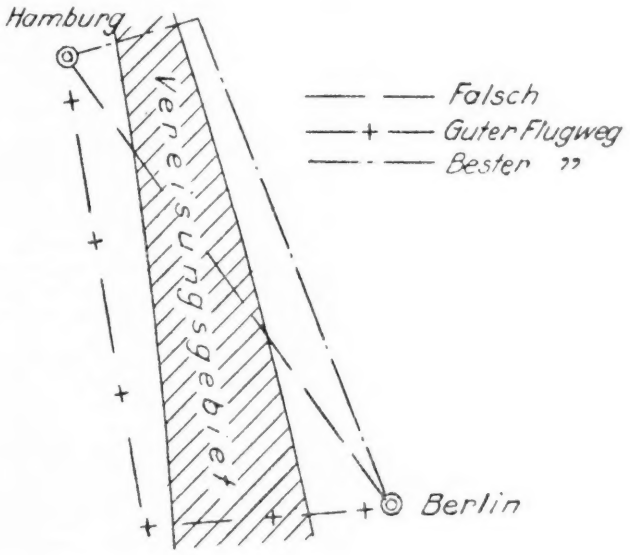


FIG. 9.

never be wholly satisfactory because there is always the risk of a certain amount of accretion.

(*b*) *Vertical Navigation.*—Better results may be obtained by vertical navigation. From Fig. 7 it is seen that a flight can be made from A to C in spite of supercooled rain by selecting a favourable altitude, without ice being formed in warm air, till reaching B it is not even necessary to fly blind.

If a flight is made in bad weather conditions, when the temperature does not exceed 0° at any height, and owing to a new inflow of cold air or a warm front, very humid cloud air and ice accretion are to be expected below, the last resort will be to get above the clouds. Frequently this succeeds at a height of 3,000 to 4,000 metres, but in most cases with weather conditions of this kind a height of 5,000 metres is necessary. In many cases even this height is not sufficient. When climbing, the regions in which the front is situated should be avoided, because there the ice formation is more intense and in some circumstances the climbing capacity of the aeroplane, owing to the incipient accretion of ice and its detrimental effect on the qualities, will not suffice to enable the aeroplane to climb through.

Numerous technical remedies have also been devised in the endeavour to meet the various difficulties.

(*c*) *Technical Remedies.*—In nearly all cases down to $-12°$ a remedy against ice accretion in nozzles has been achieved by electrical heating. The distance compass and turn indicator are most connected to the engine, the aerial can be protected with an ice protector. Ice accretion on levers and the like can be prevented by plentiful lubrication with ambroleum. The windows of the pilot's cockpit should be opened if ice begins to form. Ice can be dispersed from fast running metal airscrews by short intermittent throttle manœuvres (if the ice does not break away uniformly, however, powerful vibrations may be set up). In the case of ice forming on the generators resort is made to accumulator or indirect drive for the W./T. set.

Ice accretion on the carburettor system may be prevented by shifting the screen back and fitting devices for preheating by the exhaust. Ice may be prevented from forming on the oil tanks or in the crankcase vents by structural measures and on the radiator slats by repeatedly opening and closing them; a better plan is to move the slats behind the radiator.

Numerous attempts in various countries have been made to prevent ice accretion on the wings. The only practicable protection hitherto devised, however, in the Goodrich de-icer. All parts on which ice is likely to form (leading edges of wings and tail surfaces) are provided with a rubber covering divided into a number of compartments which can be inflated at definite intervals by means of a small air pump. Owing to the deformation which ensues the ice is broken up. Though this device does not altogether prevent ice accretion it is nevertheless effective to such an extent as to be regarded as a practical proposition.

7. Procedure in the Case of Ice Accretion.

Before setting out on a flight, if there is risk of ice accretion, the crew must be sure about the condition of the aeroplane, the general state of the weather and the route. Emphasis must be laid on the general state of the weather. Individual reports are not in themselves sufficient. A general survey is necessary in order to have a loophole in the event of bad weather conditions becoming worse or a severe and rapid accretion of ice. This loophole must be assumed with due regard to all unfavourable circumstances; if it is not provided the flight, in principle, should be abandoned. Before starting, therefore, a detailed discussion with the meteorological officer must be held. The crew must always be informed as to (*a*) the upper and lower limits of the clouds, *i.e.*, their thickness, (*b*) the temperatures, (*c*) humidity, and (*d*) probable changes.

The *least favourable weather conditions* with regard to ice formation are those associated with a change from frost to thaw (the most dangerous is the region between cold and warm in which a front with precipitation is developed). There are likewise so many factors associated with the surface conditions also that only a general survey is possible. Decision must be made, according to the extent and energy of the front and the locality of the aerodromes of departure and destination, as to whether flight above, through or below the front is possible. If mountain ranges have to be crossed, in most cases the question of flight below or through does not enter consideration. It must be borne in mind that, on the windward side, owing to the rising of the air masses and the clouds, intensive condensation associated with severe ice formation will be encountered. (According to experience an attempt to fly above the front necessitates reaching heights of between 3,000 and 4,000 metres; and over mountain ranges and fronts of as much as 5,000 m. or even more.) The most important factor for the decision to fly above the front is the position of the aerodromes of departure and destination relative to the front. If both lie outside, *i.e.*, in front or in the rear of the front no particular difficulty should be involved if the aeroplane has good climbing qualities and is properly equipped. If, on the contrary, one or both of the aero-

dromes is already or still inside the front, the following points should be observed with regard to flying up or down through the front; the climb should be effected at a *low forward speed* with the greatest possible rate of climb. If at a height between 2,000 and 2,500 metres there is still no sign of the upper limit, that is, if the ice accretion is such that the rate of climb slackens, it is advisable to discontinue. Any further attempt to climb is only possible when in the lower 500 metres above the ground.

There are positive temperatures, so that the ice can thaw away. The same rule applies to the glide; slow forward speed, rapid rate of descent. It should be remembered that when plunging into clouds with the aeroplane super-cooled, ice may form at a bound.

The ice accreted when climbing through cloud disappears after a short time above the clouds through evaporation. Since immediately above the upper cloud limit a high order of humidity may persist it is advisable to climb a few hundred metres more. If extensive, high reaching cumuli are met with over the front, the pilot should fly around them. He should never fly through them since sudden ice formation may safely be expected, as in all clouds of the cumulus class.

In flat country flight between the clouds may sometimes be possible. A height between 600 and 1,000 metres has been found to be favourable. Since in advance of the front the precipitation falls mostly in solid form from the higher warm front layer, in most cases no ice forms here. Ice will not accrete till the region where the aeroplane meets the ascending warm air and the precipitation appears as rain, mixed with snow. From this moment onwards the front should be traversed as nearly as possible, at right angles and simultaneously a close watch kept on the temperatures. By varying the height of the aeroplane a few times, the most favourable layer will soon be found. When flying from warm to cold, procedure should be more cautious, because a thaw later on is hardly to be expected. When flying horizontally through the clouds, ordinary speed may be maintained since otherwise another influencing factor, viz., time, would in equal measure intensify the ice accretion.

Apart from the fronts described, the upper limit of cloud during the winter is rarely more than 2,000 metres high. With relatively high barometric pressure, extensive bad weather conditions with the following characteristics are very frequently found:—

Lower limit of cloud at 100 m.
Visibility 1 to 2 km. and less.
Temperature round about 0°C.
Drizzle or soft hail at intervals.

In this case it is a matter of low clouds which, in part, may be regarded as high fog. The upper limit of cloud is rarely higher than 800 to 1,000 metres. Above this there is no cloud and generally an inversion of temperature. Flight upwards through the cloud presents no difficulties. Ice forms more or less intensively in the last 200 to 300 metres below the upper limit only. On approaching the aerodrome of destination this relatively large risk of ice accretion at the upper limit of the cloud should be borne in mind and the approach made at as low a height as possible. If slight precipitation is falling, the humidity in the lower layers as well will naturally increase through the extra moisture. In such cases, where a relatively high order of humidity is encountered in the lower layers, together with the risk of ice formation, special caution should be exercised and if necessary the flight abandoned, particularly when an approach has to be made by the ZZ procedure.

Whereas by day it is possible easily to observe the progress of the ice accretion it is not directly possible by night. A simple means of keeping watch on the thickness of the ice is to fit a small profile outside the fuselage within range of the pilot.

The most dangerous kind of ice formation, it should be repeated, is " super-cooled rain," sometimes also called " ice rain." (Ice rain is defined by meteorologists as a precipitation of frozen rain drops, hence, or ice grains, which in themselves are harmless.) If an aeroplane encounters super-cooled rain of this kind, the pilot should immediately get away from this region, since to remain in it or to continue flight in it is highly dangerous and may lead to disastrous consequences.

Ice may form on the aeroplane on the ground through rime, rain and snow. In principle, before taking-off, it should be completely removed from the aeroplane, after which the control system should be tested without fail to see that it is in proper working system/order.

The meteorological aspects described in the present paper apply in many respects to Central Europe only or to regions with similar climate. In other regions they differ considerably in some cases.

NOTE ON THE POSSIBILITY OF FLIGHT BY HUMAN POWER

By H. C. H. Townend, D.Sc., F.R.Ae.S.

The object of this note is to draw attention to a few facts which, taken together, suggest that, from a purely aerodynamic point of view, the difficulties involved in flight by human power may not be as great as is generally supposed.

Some years ago, in a lecture delivered to the Royal Aeronautical Society, the German soaring pilot, Lippisch, referred to an account of dynamic soaring given by Lanchester in his "Aerodonetics" and to some wind tunnel experiments made in Vienna. Lippisch makes the following observations:—*

"Let us now assume the air to be in such a motion of oscillation (*i.e.*, a vertical oscillation) due to friction with the earth's surface or to variously moving air masses. By flying through this air in an aircraft with stationary wings the above-mentioned vibration effect would occur. As both forward thrust and lift result, it must be clearly possible to soar in such layers without the help of actual upwind. This effect, which is caused by the periodically changing vertical speed of the wind, is called the 'Knoller-Betz effect.'"

Later he says:—"It is obvious that horizontal oscillations of the wind could cause similar effects. Consider for a moment a wing flexibly mounted on a fuselage. A strengthening of the wind would cause an upward movement of the wing, and by means of the energy collected in the sprung connection, a forward thrust could be exerted in the following lull by means of the downward beat of the wing. The motion of the wing is thus caused by the pulsation of the wind, so one can consider the aircraft as 'an aircraft driven through wind pulsations by wing beats.' This effect which, as far as I know, was first discussed by W. Birnbaum (Z.F.M., 1924, p. 128), reveals a number of matters connected with the performance of cantilever sailplanes of large span in very gusty winds. *The superiority of this type over the stiff-winged braced types is very striking.* Nevertheless, the effect is very small, and is only of secondary importance as compared to upwinds. In spite of this it is, in my opinion, not wise to ignore this dynamic soaring flight entirely."

In view of the *experimental* evidence implied in the remarks (which has been underlined) in the above quotation, the writer attended an informal lecture given on the 14th February, 1936, by another well-known German soaring pilot, Kronfeld, before the Institute of Mechanical Engineers on the subject of soaring. No reference was made during the lecture to the present question until it was raised by the writer during the discussion, when he asked Herr Kronfeld if he had made any similar observations. His reply was to the following effect:—"In fairly calm conditions there was no difference in performance between the rigid and flexible types of wing structures, but in gusty weather the flexible type showed greater efficiency in that greater heights were more easily obtained than with a braced wing machine." The phenomenon itself, therefore, is well authenticated and bears out Lippisch's observations.

It is recognised of course that, so far, the facts mentioned relate to extracting energy from masses of air which are moving relatively to the air as a whole, *i.e.*, to available energy in the air. It is remarkable that so small an amount of flapping as is involved in the unavoidable flexure of a structure designed to

* Journal of Roy. Aero. Soc. "The Development, Design and Construction of Gliders and Sailplanes." July, 1931, pp. 549-551.

behave (aerodynamically) as though it were rigid should yield results great enough to make a "very striking" difference to the performance. This suggests that by varying the application of the principles involved it may be possible to supply, by human agency, sufficient extra energy to a sailplane to maintain it in the air for short periods when up currents are not available. This might provide the pilot with a means of converting a glorified glide, whose course is, to a great extent, determined by prevalent geographical or meteorological circumstances, into a flight which is largely under his own control; and thus enable him to get from A to B instead of merely enjoying himself in the neighbourhood of A.

Several years ago Cowley reviewed some work that had been done on "the Katzmayr effect,"* which has a bearing on the present subject. A fixed aerofoil was placed in an airstream which was made to change its direction periodically by a series of oscillating guide vanes in the inflowing air. Negative drag was obtained up to fairly large values of lift coefficient. This case may be regarded as an inversion of flapping flight where the energy is given to the air instead of to the wing, with the important difference, however, that there is no related periodic twisting of the wing. Cowley calculates, however, that if such a change in wing angle is combined with the oscillating airstream a very large improvement is obtainable, provided the phase relationship between the oscillations is suitably adjusted. Finally, when both oscillations are applied to the wing, we have flapping flight proper.

The curves given by Lippisch in the paper cited apparently refer to the same tests as those quoted by Cowley; from them it appears that a thick wing section is much more suitable than a thin one.

It is interesting to note that Cowley concludes by suggesting that the performance of an aeroplane should be better in bumpy weather than in a calm, provided the wind waves are long compared with the chord. Kronfeld only finds this to be the case, however, when the wings of his glider are flexible.

Some further information given by Herr Kronfeld is of interest. He states that a good sailplane may have a sinking speed as low as 1 foot per second with a gliding angle between 1 : 20 and 1 : 30, requiring only 1.5 h.p. to keep it aloft in still air, and that as a man may exert 2½ h.p. for short periods, it appears not fundamentally impossible that he should be able to keep himself aloft long enough to get from one soaring area to another situated in the direction in which he wishes to fly. As the above figure of 2½ h.p. for the power available seemed remarkably high, the writer sought corroboration from Prof. A. V. Hill, who kindly supplied the following information.† A vigorous man in good health can exert about 0.38 h.p. continuously, while for a few minutes an athlete, running uphill, can probably exert about 1½ h.p. The "performance" of a boat race crew has been measured by towing the craft, with crew aboard, and from this the h.p. has been obtained as about 0.5 for a period of twenty minutes. A sprinter, running at top speed for about 20 seconds can develop about 2.6 h.p. during that time; but he would be completely exhausted at the end, and unfit for further effort for 20 minutes or so.

It is important that as much of the musculature as possible should be used, and therefore pedalling, as ordinarily understood, would not be very satisfactory.

Physiologically it appears that the way in which the human body can most efficiently convert its energy into motion is by employing a mechanism similar to that involved in rowing. The problem is, first and foremost, one of transferring with the greatest efficiency possible, the small available power to the air. If the wings could be designed to have a natural period of oscillation commensurate with that at which the rowing cycle of operations can conveniently be

* R. & M. 969. A note on the "Katzmayr Effect," that is, the effect on the characteristics of an aerofoil produced by an oscillating airstream.

† Further information is contained in a lecture delivered by Prof. Hill on 29th November, 1935, to the Institute of Mechanical Engineers.

made, it seems likely that good aerodynamic efficiency could be attained. This kind of flapping flight would appear ideally efficient since propulsion would be provided by what is virtually an airscrew having a large diameter (effectively equal to the span) and without any resistance.

Probably the best hope of success lies in a two-seater machine—an aerial tandem, but even if human propulsion proves impossible it seems likely that the proposed scheme would be more efficient for an engine assisted glider, than one using a small diameter airscrew, and it is thought the scheme might be worth theoretical investigation.

It is suggested that the aerodynamic conditions necessary should be examined mathematically along lines similar to those involved in the study of flutter. Torsional and flexural oscillations would appear to be essential, and the problem seems mainly one of deciding where the axis of torsion should be, and the relation between torsion and bending.

Even if the structural difficulties should appear great, it would seem to be worth while to know whether it is fundamentally possible to transfer the necessary power by the mechanism in question, without using the large amplitudes of oscillation generally associated with the usual proposals for flapping flight.

ABSTRACTS AND NOTICES

FROM THE

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(Prepared by R.T.P.)

No. 44. JUNE, 1937.

On the Mapping of the Velocity Potential and Stream Functions of an Ideal Fluid. (A. C. Erickson, Science (N.S.), Vol. 81, No. 2098, 1935, pp. 274-275; Phys. Berichte, Vol. 17, No. 1, 1/1/36, p. 10.) (44/1 2310 U.S.A.)

A new electrical process for determining the stream lines in the case of a two-dimensional potential flow is described. The shape of the body under investigation, round which the flow passes, is either cut out from a sheet of electrically conducting paper (black paper) or is made from good conducting material and laid on this paper. By touching this paper with electrodes, equi-potential lines can be traced, using a galvanometer. The method also permits the velocity field to be determined quantitatively.

The Effect of Pressure upon Natural Convection in Air. (O. A. Saunders, Proc. Roy. Soc., Vol. 157, No. 891, 2/11/36, pp. 278-291.) (44/2 3366 Great Britain.)

Many experimenters have determined the effect of l (representative length) and θ (representative temperature difference) upon the heat loss from surfaces to the surrounding atmosphere, but the effect of pressure has not been investigated systematically except in one particular case. The present paper describes measurements with vertical plane surfaces of four different heights in air at pressures from 0.001 to 65 atm. It is shown that the results can be expressed satisfactorily in terms of a dimensionless number and the values are given over a wide range. Natural convection at higher pressures, up to 1,000 atm., is also discussed and results for a hot wire in N_2 are mentioned.

General Laws of Natural Convection. Conditions for the Appearance of the First Régime. (P. Vernotte, Compt. Rend., Vol. 202, No. 9, 2nd March, 1936, pp. 733-5.) (44/3 5419 France.)

Attention is drawn to the difficulty of deciding when the laws for natural convection cease to hold and should be replaced by those for forced convection. Two cases are examined theoretically—that of a fluid contained in the space between two concentric spheres and that of a horizontal cylinder. For the latter case the transition should occur when Péclets number has a value of about unity and experiments are in agreement with this.

Smoke Method for Rendering Flow Visible Round Obstacles. (J. Valensi, L'Aeron., No. 213, Feb., 1937, pp. 17-26.) (44/4 5558 France.)

The smoke (air charged with NH_4Cl) is emitted either in the form of a continuous jet at the speed of the air stream, or in puffs of regulable frequency, with the aerodynamic field to be studied. The smoke is observed either stroboscopically, by means of light from the " Stroborama " (in the case of intermittent emission of smoke the light is modulated at the same frequency), or continuously by a beam of light. The phenomena can be photographed in both cases and observations have been made without difficulty at air speeds up to 80 m./sec. Illumination by the " Stroborama " has enabled marginal vortices of propellers and wings to be photographed. Continuous illumination is employed for determining the direction of velocities in permanent or semi-permanent flow. The application of the method to various problems is described and the results illustrated.

On the Response of a Vane Anemometer to an Air Stream of Pulsating Speed. (E. Ower, Phil. Mag., Vol. 7, No. 157, May, 1937, pp. 992-1004.) (44/5 6027 Great Britain.)

The behaviour of a vane anemometer in a pulsating air stream is examined theoretically. It is shown that the anemometer over-estimates the average air speed, and an expression is given for the magnitude of the error in an air current whose speed pulsations follow a sine law. In order that the equation of motion may be integrable analytically a small term is neglected, and this step is shown to be justified by comparing the approximate solution with the results of numerical integration of the complete equation of motion. The response of a particular vane anemometer to a pulsating air stream has been observed in the wind tunnel, and the results of the experiments confirm the theoretical conclusions.

On the Influence of the Ground on Lifting Airscrews. (A. Betz, Z.A.M.M., Vol. 17, No. 2, April, 1937, pp. 68-72.) (44/6 6110 Germany.)

On the basis of simple considerations, the effect of the ground on the motive power producing a given thrust is determined for the case of a lifting screw at a small or large distance from the ground and the result is represented graphically. The expression deduced is also used to determine the effect of the ground on the thrust at a given speed of rotation and finally it is shown how the effect of additional propeller losses can be taken into account.

The Second Invariant of the Tensor of Deformation. (M. Lagally, Z.A.M.M., Vol. 17, No. 2, April, 1937, pp. 80-4.) (44/7 6112 Germany.)

In the motion of a viscous fluid, as defined by the fundamental equations of Euler and Stokes, the deformations form a tensor whose well-known invariants are the divergence and the curl. Of equal interest, but more difficult of interpretation, is the " second invariant," which plays an important part in the dissipation function. The " second invariant " occurs among the geometrical invariants of the field of velocities of a compressible fluid and is treated by Hamel.

Conformal Transformation with the Aid of an Electric Tank. (K. N. E. Bradfield, S. G. Hooker, and R. V. Southwell, Proc. Roy. Soc., Series A, No. 898, 1/4/37, pp. 315-346.) (44/8 6155 Great Britain.)

There exists a well known analogy between the stream function of an inviscid fluid and electric potential. Similar harmonic functions appear in many elasticity problems, but usually the boundary conditions are difficult to satisfy in the electrical experiments. The authors, however, point out that the solution obtained with a conducting boundary can be used to give the required information by

conformal transformation. The method is illustrated by applying it to the study of the torsion of an isotropic prism with an equilateral triangular base. The results obtained are in excellent agreement with those obtained by the elastic theory and it appears that the electric tank can be put to a wider use than has hitherto been contemplated.

Study of the Flow of Air in the Immediate Neighbourhood of a Wall. (L. Sackmann, Compt. Rend., Vol. 204, No. 18, 3rd May, 1937, pp. 1313-5.) (44/9 6201 France.)

A stream of chemically active fluid passing in the neighbourhood of a suitably sensitised wall can produce a chemical reaction accompanied by a colour change, thus tracing on the surface the local direction of flow. The following points are to be noted:—(1) The reaction must not alter the roughness of the wall. (2) From the point of view of a rapid reaction it is advisable to use a coloured indicator for sensitising the wall, a gaseous reagent (acidic or basic) being contained in the fluid. (3) The traces obtained must be stable and correspond to the flow phenomena without deformation or diffusion. The method has been applied to the study of flow round a cylinder and over aeroplane wings; in the latter case a model (Göttingen profile 433, Reynolds number 88,000) being used. A figure shows the results obtained with the wing at an incidence corresponding to a stall ($i = 15°$). It is known that the sudden decrease in lifting properties of a wing is accompanied by complete change in the condition of flow over the upper surface, and that the line of commencement of turbulence is very far forward towards the leading edge. By this method its location can be determined exactly, and the surprising result is obtained that it remains rectilinear and extremely clearly defined, in spite of the turbulent nature of the flow on the upper side.

Laminar and Turbulent Boundary Layers as Affecting Practical Aerodynamics. (E. N. Jacobs, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 44.) (44/10 6214 U.S.A.)

The aerodynamics of aerofoil sections are considered with special reference to the determination of where transition from laminar to turbulent flow takes place along the aerofoil surface.

There being no experimental equipment for studying the problem in the higher full-scale range of Reynolds numbers, two theoretical methods have been tried. In the first method the laminar boundary layer is supposed to become unstable. In the second the mechanism of transition is supposed to be something like separation, this comparison having the advantage that the separation phenomenon is comparatively well understood and can be dealt with quantitatively by existing theory. Separation and its relation to the transition phenomena are therefore considered and the actual behaviour of the flow during its change from laminar to turbulent is illustrated. Suitable equipment capable of reaching very large Reynolds numbers will be necessary to ascertain whether the theoretical gains indicated by the theory are possible in practice.

The Dynamics of Large Hailstones. (E. G. Bilham and E. F. Relf, Quarterly Journal of the Royal Met. Society, Vol. 63, No. 269, April, 1937, pp. 149-162.) (44/11 6341 Great Britain.)

The form of the relation between terminal velocity and diameter of the hailstone is deduced from values of the drag coefficient obtained from observation on spheres towed by aeroplanes. Values of the terminal velocity are calculated for various mean densities of the ice and it is concluded that an upper limit of about 1.5lb. is set to the possible mass of a spherical hailstone by aerodynamic considerations. The terminal velocity under these conditions is of the order of 180 feet/sec.

Recent Research in Aircraft Structures. No. II. (D. Williams, Engineer, No. 4231, 5, and 12/2/37, pp. 153-4, 177-180.) (44/12 4712 Great Britain.)

Recent work in aeronautical structure research, of general interest in other branches of structural engineering, is described. Problems dealt with are:—

1. A tube of rectangular cross section under torque loads.
2. Tubes and channels subjected to bending without twisting.
3. The Hardy-Cross method of solving rigid-jointed frame problems:—
   (*a*) The original demonstration by Prof. Hardy-Cross.
   (*b*) The Hardy-Cross method applied to the continuous beam.
   (*c*) The Hardy-Cross principle in relation to the plane braced frame with rigid joints.
4. The design of beams by Wagner's tension field theory.
5. The synthesis and analysis of simply stiff structures.

Thirteen references.

The Fuelling of Land- and Seaplanes. (J. Retel, L'Aeron., No. 212, January, 1937, pp. 9-15.) (44/13 5054 France.)

Stationary refuelling depots usually consist of large underground sheet iron tanks, embedded in concrete, and filled by gravity from tank wagons, etc. Mobile depots consist of tank lorries, etc., equipped with fuel pumps, filters and fuel gauges. For military purposes vehicles must be able to traverse any type of ground and a number of light lorries is preferable to a few large tank wagons owing to the time saved by simultaneous refuelling of a number of planes.

In actual refuelling of a plane speed and safety are the main considerations. At no time must the fuel be in contact with air and at the end of the operation there must be no overflow from the tank. To ensure rapid filling the diameter of pipes must be as large as possible without reducing manœuvrability, and high pressure may be employed. The speed of flow is limited by the necessity for filtering and the danger of formation of charges of electricity. The above requirements are met by the following conditions:—(1) Maximum diameter of the pipe feeding the fuel tank—45 mm. (2) Pressure about 1 kg./cm.^{2} for a difference in level of 3 m. between the level of the aeroplane tank and that of the pump. (3) Speed of flow about 3 m./sec. The main difficulty of tightness of the connections between pipe and tank has now been overcome. The Rellumit rapid connecting system is shown diagrammatically. Flow is stopped automatically when the tank is full.

Wind Tunnel Tests of a Clark Y Wing with "Maxwell" Leading-Edge Slots. (W. E. Gauvain, N.A.C.A. Tech. Note No. 598, April, 1937.) (44/14 6028 U.S.A.)

The Maxwell type of leading-edge slot differs from the Handley Page slot in that the moving parts operate solely by rotation. The Maxwell slot also provides a means for producing an unbroken leading-edge contour when it is in the closed condition. Experiments on a Clark Y wing fitted with the Maxwell slot were carried out in the N.A.C.A. 7 × 10-foot channel on a wing 60 inches span and 10 inches chord at an air speed of approximately 80 m.p.h. The performance of the device depends on the width of slat. With a wide slat (chord 3 inches) and trailing edge flap (60°) C_L max. = 2.53. With a narrow slat (1.75 inches) and no flap, the performance of the wing was approximately the same as when fitted with a Handley Page slot of the same slat size, except that the gliding angle of the Handley Page device is approximately 30 per cent. steeper. A common disadvantage of all slotted type of wings is the high angle of attack at which C_L max. occurs. This means that a combination of flaps and slots will have to be used for landing.

Vibration Phenomena in Ternary Wing Flutter. (K. Sezawa, S. Kubo and H. Miyazaki, Aer. Res. Inst., Tokio, Report No. 147, April, 1937, 40 pp.) (44/15 6187 Japan.)

The present paper is an extension of two preceding papers to a more general case of ternary flutter, including the special cases of binary and unitary flutters. The character of the flutter was ascertained, mathematically and experimentally, through its vibrational frequencies and amplitudes for any wind velocity. The fact that flutter is a condition of unstable vibration, but not a resonance phenomenon due to turbulence of wind, was confirmed by comparing the mathematical solution of the free and forced vibrations. From model experiments it was confirmed that, while in the stage where ternary flutter begins, namely, the stage of lower wind velocity, the vibrations are merely of deflectional type; in the secondary stage, namely, the stage of higher wind velocity, they are almost torsional. The present investigation suggests that by use of a vibration damper consisting of a suitably selected inertia mass and elastic as well as damping resistances, it will be possible to raise the critical speed for wing flutter to any extent, besides minimising the vibration amplitudes even in its flutter state.

Measurement of Vibration in Flight. (C. S. Draper, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 44.) (44/16 6212 U.S.A.)

The M.I.T.-Sperry apparatus for measuring vibration in aeroplane structures and power plants during actual flight is described. This has been developed as a result of a co-operative research programme carried out by the Bureau of Aeronautics of the U.S. Navy and the Massachusetts Institute of Technology, with contributions to design by the Sperry Gyroscope Co., Inc., and consists essentially of a number of electrical pick-up units operating a central amplifying and recording unit. The recorder is a double-element photographic oscillograph. Each pick-up is specially adapted to the type of vibration which it is intended to measure and is made so small that it does not appreciably affect the vibration characteristics of the member to which it is rigidly attached. By using a number of systematically placed pick-ups, all necessary information regarding vibration on an aeroplane can be recorded during a few short flights. The following are described in detail:—Flight test installation, sample records and results from flight test, measurement of vibratory strains, pick-up units, strain-gauge, amplifier, oscillograph and calibrator.

The Practical Application of Fowler Flaps. (F. D. Fowler, Paper to S.A.E., Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 44.) (44/17 6215 U.S.A.)

Practical design procedure for obtaining the most efficient characteristics of the Fowler high-lift wing device is dealt with. Points discussed include:—The importance of location of tail surfaces, the need for greater control power in the case of large aeroplanes using flaps, normal and horizontal forces in Fowlers, their reduction in a new type of aerofoil section and consequent influence on the weight of the complete flap installation. The trend towards high wing loading limits the use of slit flaps, but the limit may be extended by the use of Fowler's of 15 to 40 per cent. chord, the maximum lift increasing with chord size. Advantages of Fowler's in take-off and landing, with reference to the possible use of the nose wheel and the effect of the slipstream on the flap are pointed out. Emphasis is placed on the need for a spare wing (Fowler flap) as an extra safeguard in case of partial engine failure, ice formation or in emergency landings.

Longitudinal and lateral controllability is not necessarily reduced by Fowler's as compared with the requirements for the basic aeroplane.

Three-Wheel Landing Carriage of the Douglas DC.4. (Les Ailes, No. 831, 20/5/37, p. 7.) (44/18 6268 U.S.A.)

This new 40-seater aircraft is to be fitted with three landing wheels, one near the nose of the aircraft and the other two below the wings. The wheels are orientatable in all directions, the design being similar to that developed by the N.A.C.A. for light aircraft. Cross wind landings are thus possible and the tail being always off the ground, the attitude of the machine remains horizontal when coming to rest and the comfort of the passengers is increased. In order to concentrate the propeller slipstream on to the tail surfaces the engine axes are not parallel, but radiate outwards. The wing structure follows that of the Junker G.31, in that it is carried through the floor of the passenger cabin, the hollow wing space being utilised for luggage space.

Giant Flying Boat—Boeing 314. (Inter Avia, No. 428, 1/5/37, pp. 4-5.) (44/19 6331 U.S.A.)

This flying boat, which will be ready by the end of the year, weighs 30-40 tons and will be equipped with sea wings and fitted with four Wright engines of 1,500 b.h.p. each.

The new boat follows the general lines of the Martin Clipper, but will carry 72 passengers and a crew of eight as well as 5,000lb. of cargo. The boat has three decks, a top deck with the flight bridge and accommodation for the crew, a main deck for passengers and a third deck or hold consisting of a series of watertight compartments. This deck also contains the main fuel tanks (14,000lb.) and the freight. Additional fuel tanks (1,000lb.) are placed in the wings and sponsors.

The expected speed is 200 m.p.h. and the range 5,000 miles.

The Future of the Airship. (F. W. Lanchester, Engineering, Vol. 143, No. 3724, 28th May, 1937, pp. 613-4.) (44/20 6353 Great Britain.)

Doubt is expressed as to whether the airship has any prospect of a commercial future. Safety can be ensured only by inflation with helium, and in the case of the Hindenburg, this would have reduced the lift by 14 tons, equivalent to two-thirds of the pay load, and the airship would then have had no commercial value. It is stated that had the R.101 been filled with helium it would have been unable to rise from the ground at all. By comparison, over a flight of 12,000 miles, of the performance of an airship, with that of the probable future type of aeroplane (four Diesel-engined flying boat, of speed 200 m.p.h. and capable of undergoing minor repairs in flight) it is shown that allowing four 8-10-hour stops of the flying boat, it can still cover the distance in 100 hours, as against an estimated non-stop journey of 150 hours by the airship. There is no prospect of increasing the speed of airships beyond 100 m.p.h. unless their size is considerably increased.

Comparison of Combustion and Working Processes of Various Types of Internal Combustion Engines. (E. F. Schmidt, Z.V.D.I., Vol. 80, No. 25, 20/6/36, pp. 769-779.) (44/21 1901 Germany.)

Indicator diagrams have been obtained by means of the D.V.L. glow-lamp indicator, and special interest attaches to the diagrams for pressure differences between the various parts of the sub-divided combustion space of new types of Diesel engines. In particular the relationship between fuel consumption and mean and maximum pressure in the cylinder is explained and the effect of ignition lag on the pressure curve and progress of combustion investigated. The processes in a Diesel engine with sub-divided combustion chamber are more closely investigated, and the effect of differences in wall temperatures are noted.

Piston Ring Friction in High Speed Engines. (L. Illmer, Trans. A.S.M.E., Vol. 59, No. 1, January, 1937, pp. 1-6.) (44/22 4578 U.S.A.)

The recent trends towards higher speeds in internal combustion engines has been accompanied by a sharp rise in frictional losses due primarily to abnormal piston ring drag. The problem is of particular importance in multi-cylinder engines of small bore in which the ratio of the combined contacting surface of the sealing rings to the piston area is unduly large. The increased drag is due to a relatively high pressure which is built up in the annular chamber under the first, or top, ring. Available test data from different sources is collected in this paper and analysed to establish a criteria for normal frictional drag at different speeds and groove pressures. Results are used to predict the piston ring friction of a heavily loaded engine running at maximum speed.

Hydraulic Starter for Aircraft Engine. (Autom. Ind., Vol. 76, No. 17, 24/4/37, p. 622.) (44/23 5969 U.S.A.)

Mounted opposite the end of the crankshaft, the Berger starter consists of two opposed cylinders, each containing a piston with a stem having an inclined rack. The central helicoidal pinion engages with the two racks. The oil, maintained under high pressure in a small tank, is admitted into the cylinders by means of a three-way cock operated from the instrument board. By reason of the thrust, the pinion moves forward, engaging with the claw on the end of the crankshaft and turns over the engine by reason of its rotation. At the end of the stroke the pinion disengages and the two racks return to their original position by reason of the coil springs. A spring-loaded ball locks the pinion in the central position. The oil used for the starting motor can also be employed for operating the landing carriage, brakes, or other parts of the plane.

Blower Cooling of Finned Cylinders. (O. W. Schey and H. H. Ellerbrock, N.A.C.A. Report No. 587, 1937.) (44/24 6029 U.S.A.)

Several electrically heated finned steel cylinders enclosed in jackets were cooled by air from a blower. Tests were conducted at air velocities between the fins from 10 to 130 m.p.h. and at specific weights of the air varying from 0.046 to 0.074 pound per cubic foot. The fin dimensions of the cylinders covered a range of fin pitches from 0.057 to 0.25 inch, average fin thicknesses from 0.035 to 0.04 inch, and fin widths from 0.67 to 1.22 inches. The value of a, based on the difference between the cylinder temperature and the inlet air temperature, varied as the 0.667 power of the weight velocity of the cooling air for cylinders having fin spaces from 0.21 to 0.077 inch. The smaller spacings, the exponent increased and the value of a decreased. The power required for cooling varied as the 2.7 power of the weight velocity for a given density and inversely as the air density for a given weight velocity. For a given power, maximum heat transfer was obtained with a 0.045 inch spacing.

Aircraft Engine Reduction Gears. (F. L. Prescott, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 46.) (44/25 6218 U.S.A.)

A brief history of the development of military aircraft engines shows the necessity for the development of reduction gearing. Seven general types of reduction gears which have proved satisfactory for aircraft engines are described with diagrams, and their advantages and disadvantages discussed.

As regards stresses in crank cases and engine mounts, it is shown that crank case torque stresses are greatly reduced if the direction of rotation is the same for the crankshaft and the propeller shaft. Advantages of the use of two propellers rotating in opposite directions on the same engine are discussed, with two suggested methods for gearing the propellers. Mention is made of the advantages of optional propeller rotation on multi-engine installations, methods

of equalising both loads in multiple contact types of gearing, optimum propeller shaft speed, engine speed and reduction gear ratio.

Design Tendencies in French Aeroplane Engines and Propellers. (H. L. Brownback, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 50.) (44/26 6222 U.S.A.)

The French originally built air-cooled engines almost exclusively, but were forced to change to water-cooling (of both V and radial types) during the war. During that period they developed superchargers and the "cannon" engine firing 20 mm. shells through the propeller shaft. Since then development has not been confined to any one type and they now have water-cooled V engines developing 1,200 b.h.p., radial air-cooled engines up to 18 cylinders giving 1,000 b.h.p., and high speed "in-line" and V type engines turning up to 5,200 r.p.m. and developing over 1 b.h.p. per cu. in. displacement. Both water-cooled and air-cooled radial Diesel engines developing 600 b.h.p. have been constructed and flown. Variable pitch propellers are being developed in several models and some interesting types are being worked out. It appears that the propeller and not the engine will soon be the limiting factor in the development of power plant.

The Sklenar Double Rotary Engine. (Les Ailes, No. 832, 27/5/37, p. 7.) (44/27 6346 France.)

This radial engine resembles the differential engine of Siemens (1918), in that the crankshaft and cylinders rotate in opposite direction, the cylinders turning at 1/9 the shaft speed.

The novel feature of the present design consists in making the cylinder heads stationary and in ring form.

The cylinders rotate inside the common circular head, the seal being provided by a conical washer and sealing pads.

The common head is provided with inlet and exhaust ports which are operated by the over-running of the cylinders, the induction and exhaust thus taking place along the cylinder axis.

This arrangement obviates all subsidiary valve gear and it is claimed that the common stationary head can be readily cooled by the slipstream whilst the barrels are cooled independently by the rotation.

The design appears of interest especially for large power units, and it is stated that the French Air Ministry have placed an order for 20 engines.

Colloidal Graphite and Piston Ring Wear. (Autom. Ind., Vol. 76, No. 21, 22/5/37, pp. 766 and 782.) (44/28 6448 U.S.A.)

The engine was run for 15 minutes and then allowed to rest 15 minutes, this cycle being repeated 180 times. During the first five minutes of each period the engine ran light (wall temperature gradually rising to 122°F.). The remaining 10 minutes were run at full load (wall temperature 212°F.). The ring wear was obtained by weighing and in case of a new engine, the wear can be approximately halved by adding colloidal graphite to the oil.

European Trends in Automotive Diesel Design. (Autom. Ind., Vol. 76, No. 21, 22/5/37, pp. 779-781.) (44/29 6457 U.S.A.)

The following are the conclusions:—

(1) Rigidity of structure necessitates cast iron crank cases.
(2) Piston rings of tapering section in the two upper grooves are a cure of ring sticking.
(3) All bearing shells must be set in the housings so as to reduce deformation under load to a minimum and excessive tension of the bearing bolts must be avoided.

(4) Composite bearings combining the load carrying capacity of lead bronze with the dirt accommodating properties of babbit have given good results.

(5) Cylinder head temperatures are best controlled by directed water supply and the water jacket should extend well below the lowest point reached by the rings so as to increase piston cooling.

Supercharger Control (*German Patent No.* 460,703, *Brand Motor Works*). Aircraft Eng., Vol. 9, No. 100, June, 1937, p. 174.) (44/30 6474 Germany.)

A multi-stage blower for charging aircraft engines is provided with a rotary valve which may be adjusted from the position in which the inlet of air from the valve to the suction conduit of the fan is cut off and air is supplied through a restricted opening to the conduit leading to the second impeller. The valve is constructed in such a manner that the opening leading to the conduit is increased until it is wide open, after which it begins to reduce again. The inlet to the conduit is then cut off from the interior of the valve, and the conduit is opened fully, in which case all the air supplied passes through both impellers and the full output is obtained.

The Regnier Engine. (Les Ailes, No. 829, 6/5/37, p. 6, and No. 830, 13/5/37, p. 6.) (44/31 6516 France.)

The first article gives constructional details of a light aeroplane engine rated at 60 b.h.p. (four-cylinder in-line, air-cooled, inverted, 2.8 litres swept volume, dry weight 72 kg.).

The good performance of this model has led to the design of a 12-cylinder V engine destined for lightweight fighters and described in the second article.

The following novel features are incorporated:—(1) Crankshaft bearings are held in place by steel tie rods which go through the crank case. By adjusting the tension of these rods, the free period of the crank case can be adjusted and resonance avoided. (2) Two Roots' superchargers are employed. It is claimed that their installation reduces the induction temperature. (3) Two concentric propellers driven in opposite direction by a synchronised differential gear are fitted. It is claimed that this increases manœuvrability (no reaction torque), smaller propellers can be used, and the resistance due to the slipstream is reduced since it is no longer helicoidal. The propulsion efficiency is thus increased by 5-10 per cent.

Neither the stroke volume nor r.p.m. of this new design are given, but it appears that relatively high speeds of rotation are contemplated. The design is thus an attempt to utilise in a production engine the experience gained with the high speed racing engines in the Coupe Deutsch.

High Speed Motion Pictures of Engine Flames. (G. M. Rassweiler and L. Withrow, Ind. Eng. Chem (Ind. Ed.), Vol. 28, No. 6, June, 1936, pp. 672-7.) (44/32 1688 U.S.A.)

A high speed motion picture camera has been designed for studying the ignition and combustion phenomena in a running engine. The engine is a single cylinder ell-head engine ($2\frac{7}{8}$in. bore, $4\frac{3}{4}$in. stroke, compression ratio 4.6 to 1), provided with a fused quartz plate in the cylinder head allowing an unobstructed view of the whole combustion chamber. The window is capable of withstanding the gas pressures accompanying moderate knock. The camera photographs about 30 pictures of a single explosion at rates up to 5,000 pictures per second. Film and image motion are synchronised by means of thirty lenses carried in a disc mounted on the engine crankshaft. Use of a focal plane shutter enables the time of exposure to be adjusted without decreasing the effective speed of the optical system, and enables the moving lenses to work at full aperture during most of the explosion. Pressure time curves of the explosions are recorded

simultaneously. A set of thirty photographs of a single explosion is reproduced. This shows the ignition spark, the spread of the flame through the combustion chamber, gas movements behind the flame front and an increase in luminosity of the burned gases near the sparking plug as the explosion proceeds and the pressure rises. When flame pictures photographed with this camera at a rate of 3,000/sec. are projected as ordinary moving pictures, the flame motions are slowed down over 200 times and changes can be followed easily.

The Viscosimetrical Inspection of Lubricating Oil in Service. (L. Steiner, Engineering, Vol. 141, No. 3675, 19/6/36, pp. 659-660.) (44/33 1742 Great Britain.)

Plotting of viscosity temperature curves forms the most reliable laboratory method for routine testing of different batches of lubricants or for following the changes in their properties during use. By means of the Steiner viscometer it is possible to plot a temperature viscosity curve of 25 points in about 40 minutes and only 6 ccs. of oil are required. This instrument is based on measurement of the time of rise of an air bubble through a graduated tube containing the oil. The bubble is of piston form and its length has no effect on its rate of movement. The tube is surrounded by a glycerine bath provided with a thermometer. The instrument is placed in a horizontal position to be heated by a hot plate, spirit lamp, etc., and after each measurement is inverted to allow the bubble to travel back to the bottom of the tube. Tables are provided for converting readings into Redwood, Saybold, or other units. Reasons for alteration in the properties of oils used for various purposes are briefly discussed and typical temperature viscosity curves before and after use, obtained with the Steiner viscometer, are given.

A Visual Study in a Displacement Piston Compression Engine. (A. M. Rothrock, J.S.A.E., Vol. 40, No. 1, January, 1937, pp. 22-27.) (44/34 4419 U.S.A.)

High speed cinema photography has been applied in investigating the effects of a displacer piston on air flow, and the effect of the latter on the fuel spray and flame formation in a compression ignition engine, 2,200 exposures per sec. being taken of the phenomena in the combustion chamber of the N.A.C.A. apparatus. This consists of a single cylinder test engine which is operated under its own power for a single cycle. A vertical disc combustion chamber, the sides of which were formed by two 2½in. glass windows and a single 0.020in. fuel injection nozzle were used. By using " Schlieren " photography the air flow, fuel injection and flame formation were recorded simultaneously.

By projecting the motion pictures, the phenomena can be observed at 1/150th of their actual speed. The results showed that, although the core of the fuel spray was not destroyed by air velocities as high as 300 ft./sec., the direction of the spray was changed and the spray envelope carried away by the moving air. The volume of the chamber reached by the combustion was considerably increased by use of the displacer piston. The air movement set up during the induction of air into the engine cylinder could be controlled so as to considerably assist the air flow set up during the last of the compression stroke.

Anti-Knocks and Pro-Knocks in the Combustion of Fuels. (A. V. Belov and M. B. Neumann, Nature, No. 3523, 8/5/37, pp. 798-9.) (44/35 6093 Great Britain.)

It is now generally recognised that detonation in an engine is due to an intense oxidation reaction in the unburnt charge prior to its ignition by the flame. From experiments carried out with pentane in a small bomb, the authors conclude that the unburnt charge may give rise to a so-called " cold " flame after a short induction period. This cold flame is accompanied by unstable products which

act as accelerators and may produce the familiar knock. The induction period of this flame can be increased or decreased by the addition of certain dopes (tetraethyl lead or amyl nitrite) and the chemical theory of detonation is thus confirmed.

Engines Using Hydrogen as Fuel. (B.P. 462,605.) (R. A. Erren, Engineer, Vol. 163, No. 4244, 14/5/37, p. 583.) (44/36 6138 Great Britain.)

Experiments have shown that inefficient working is due to insufficient mixing of the hydrogen and the air. Under certain conditions a cushion of unmixed hydrogen may form immediately above the piston and escape past the piston ring into the crankcase, and where there is considerable danger of it being ignited. In other cases back-firing in the air intake pipe is caused by unmixed hydrogen escaping past the valve seating and being ignited in a similar manner. To overcome these difficulties the hydrogen is injected in a tangential direction so as to assist in mixing the gases. The injection of hydrogen begins preferably immediately the inlet valve has closed—that is, at latest at 220 deg. of the cycle from inner deal centre—and ends at latest at 280 deg. of the cycle.

Direct Injection of Petrol into an Internal Combustion Engine. (A. Labarthe and A. Ponomareff, Compt. Rend., Vol. 204, No. 18, 3rd May, 1937, pp. 1316-8.) (44/37 6202 France.)

Tests have been carried out with a high speed variable compression petrol engine (having a special cylinder provided with a fuel injection device and a sparking plug) to determine the effect of direct injection of fuel into the cylinder at different stages of the induction and compression strokes. Results show that the maximum mean effective pressure was obtained when the commencement of injection was in the middle of the induction stroke and optimum fuel consumption was obtained by injection during the first part of the induction stroke. Knocking was reduced by injecting during the compression stroke. At the optimum conditions of injection as shown by the tests, a further series of tests was carried out to determine the variation in power and fuel consumption as a function of the speed of rotation, the richness of the mixture being constant. Similar tests were carried out with an engine having a normal carburettor. Comparison shows that injection of the fuel gives an increase in power, and of 12-17 per cent., and it is considered that this improvement could be further increased by better design. The decrease in specific fuel consumption is about 7 per cent.

The Value of Octane Numbers in Flight. (D. P. Barnard, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 42.) (44/38 6210 U.S.A.)

Improvements in octane number of aviation petrols are estimated in terms of the increased earning power of current type transport aeroplanes, by computing the change in earning power of a gallon of petrol as reflected in altered fuel consumptions or take-off load capacities. In general it can be said that:—

1. The revenue earning power of one gallon of petrol may be increased from 2 to 8 cents per octane number improvement, depending upon engine design and operating conditions.

2. If the improvement in octane number involves a decrease in energy content, the apparent improvement must be discounted by about two octane numbers for each one per cent. reduction in heat content below that of petrol.

3. The economic necessity for high octane number fuels is particularly apparent when long range operations are involved.

4. The increased earning power due to improvements in octane number is so great that cost cannot influence the trend towards higher octane numbers to any considerable extent.

Engine and Laboratory Tests of the Stability of Aviation Oils. (O. C. Bridgeman, Paper to S.A.E. Aeronautical Meeting, 11th March, 1937; J.S.A.E., Vol. 40, No. 5, May, 1937, p. 42.) (44/39 6211 U.S.A.)

Three types of laboratory method for testing the stability of aircraft engine oils were selected and data obtained for two of them using 22 oils. The methods were:—(1) Heating the oil with the surface exposed to the air, but without aeration, and (2) heating the oils under aerating conditions. Results were compared with engine data obtained with the same oils covering 30 hours' operation at cruising power in each case in a Pratt and Whitney Hornet engine. It was concluded:—

1. That laboratory methods can be developed which will rate the stability of oils in almost any order, depending upon test conditions.
2. Methods involving aeration of oils are much too severe and do not correlate with engine data.
3. Optimum test conditions appear to be heating without aeration at a temperature of approximately 175°C. Data obtained under these conditions correlate satisfactorily with the service performance of the oils in aero engines of moderate output.

Sunbury Knock Indicator. Cylinder Vibration Pick-up. (Autom. Ind., Vol. 76, No. 19, 8/5/37, pp. 693-4.) (44/40 6237 Great Britain.)

Tests on the C.F.R. engine have shown that during detonation, the cylinder is subjected to longitudinal strains, the mean velocity of vibration being a measure of the effect on the ear. In the Sunbury knock indicator this mean velocity is determined by securing an iron rod to the upper part of the cylinder and bringing its lower ends within a few thousandths of an inch of the pole of a magnetic pick-up. The induced current is rectified, amplified and measured in the usual effect by a thermal galvanometer. The advantages claimed for this instrument are that it is not subjected to the heat of combustion and the adjustments are not critical. Moreover, only one setting is required for the entire range of octane numbers.

Oiliness, what it is and what it means. (Aut. Ind.,Vol. 76, No. 19, May, 1937, pp. 697-698.) (44/41 6239 U.S.A.)

According to experiments carried out in the Pennsylvania State college, the absolute viscosity of lubricating oils increases with pressure, the rate of change being characteristic of the nature of the oil (*i.e.*, origin of crude).

The effect of pressure is most marked at relatively low temperature (high viscosity).

Thus with a load of 20,000lb. sq. in. the following results were obtained with two typical oils of different origin but similar viscosity characteristics (at atmospheric pressure):—

	Atmospheric Pressure.		20,000lb. sq. in.	
Origin of Oil.	Viscosity at 55 °C.	Do. at 90 °C.	55 °C.	90 °C.
Western ...	50 c.p.	20 c.p.	1800	300 c.p.
Eastern ...	50 .	20	550	170

When the oil lubricates a bearing, it thus undergoes change in viscosity due to pressure quite apart from those due to temperature and the so-called "oiliness" is an expression for the pressure sensitivity of the oil.

Relative Knocking Characteristics of Motor Fuel in Service. (J. M. Campbell, W. G. Lovell and T. A. Boyd, J.S.A.E., Vol. 40, No. 4, April, 1937, pp. 144-150.) (44/42 6325 U.S.A.)

In this investigation some of the underlying principles affecting the knocking characteristics of motor fuels in service have been studied. Briefly, the experiments indicate that the relative knocking characteristics of certain cracked petrols

with respect to straight-run petrols may be affected by the relationship of spark timing, engine speed and mixture ratio. From the standpoint of engine design the most advantageous of these variables in a given engine varies according to the nature of the fuel used. It is suggested that some of the anomalous characteristics of benzol blends are the result of vapourisation phenomena in the induction system, as also are certain " depreciation " effects which occasionally have been observed among straight-run petrols containing tetraethyl lead.

Engine Temperature as Affecting Lubrication and Ring Sticking. (C. G. A. Rosen, S.A.E. Journal, Vol. 40, No. 4, April, 1937, pp. 165-172.) (44/43 6328 U.S.A.)

The experiments were carried out in a small single cylinder Diesel engine arranged in such a way as to permit rapid inspection of piston and rings. The blow by on this unit was measured and the experiment stopped when the leakage from the crank case reached the arbitrary value of 85 cubic feet per hour. (Normal operation is characterised on this engine by a leakage of 12 to 20 cu. feet per hour.) The running time under these conditions varied between 100 and several thousand hours depending on the lubricant and the temperature conditions of the engine. It is claimed that the results are in agreement with practical experience and demonstrate the superiority of compounded oils. In the case of paraffin base oils, a high piston temperature is an advantage in certain cases, since the hotter ring groove loosens the deposits and frees the rings which have become stuck at the lower (normal) operating temperature. The question of ring sticking thus depends intimately on the piston design as well as on the type of oil used.

Properties of Synthetic Lubricating Oils from Kogasin. (H. Koch, Brennst. Chem., Vol. 18, 1937, pp. 121-7; Brit. Chem. Absts. B., Vol. 56, May, 1937, p. 408.) (44/44 6378 Germany.)

Lubricating oils prepared from the olefines in kogasin by the action of anhydrous Al Cl_3 have flat viscosity temperature curves; and for the same viscosity index they have a higher mean molecular weight than paraffin base mineral lubricating oils. Olefinic linkings in the oils are readily hydrogenated and the viscosity index of the product is thereby increased. The oils are as stable towards air and light at room temperature as are mineral lubricating oils, and their stability is increased by hydrogenation. Subjected to the British Air Ministry oxidation test the oils show a greater increase in viscosity index but a smaller increase in Conradson carbon than do mineral lubricating oils; no asphalt separation occurs with the kogasin oils. Hydrogenation of an oxidised oil restores its original properties to a considerable extent. The kogasin oil behaved satisfactorily in a road test. The less viscous synthetic oils have a high dielectric strength and are suitable as insulating oils.

Mechanical French Diggers and their Influence in Aerial Warfare. (Revue de l'Armee de l'Air, No. 93, April, 1937, pp. 383-389.) (44/45 6348 France.)

The mechanical diggers described will construct and subsequently fill in a trench 80 cm. deep and 15 to 30 cm. wide at the rate of approximately $\frac{1}{2}$ km./hour. At the moment such devices are principally employed for laying electric power cables, but the author points out possible applications of special aeronautical interest :—

(1) Drainage of aerodromes.
(2) Burying telephone cables.
(3) Protecting combustible material or ammunition against aircraft attack.
(4) Protecting troops on the march or in camp by providing shelter when attacked by aircraft.

Problems of Anti-Aircraft Fire Control. (P.E., Revue de l'Armee de l'Air, No. 93, April, 1937, pp. 461-471.) (44/46 6349 France.)

The author gives a summary of published information from Swedish, German and American sources. During the great war, it took between 600 and 6,000 AA shells to bring down one enemy aeroplane. According to some tests carried out in 1931 with 75 mm. Vickers' gun on a towed target moving at an altitude of 6,000 feet, at 175 m.p.h. and a distance of three miles, 40 per cent. hits were recorded (target 10 × 2 m.).

As most of the bombing raids will be carried out at night, effective co-operation with searchlights forms the major problem of AA fire control and reference is made to a paper by Col. Grove-White (Royal United Service Institution, February, 1936) as giving representative British opinion.

The article concludes with solutions of certain tactical problems published in the German Militar-Wochenblatt (No. 2, 3 and 17, 1936).

It appears that the main difficulty in AA defence is its comparative lack of mobility.

Radio Typewriter for Aircraft. (Inter. Avia., Nos. 426-427, 27/4/37, p. 4.) (44/47 5962 U.S.A.)

Tests are being carried out aboard aeroplanes by American airlines with the "Facsimile" reception machines. Similar experiments were made by T.W.A. approximately a year ago. The "Facsimile" apparatus was developed by the Radio Corporation of America. In the case of aeroplanes, only the reception apparatus is installed so that the crew will be able to receive written instructions from the ground. The transmitting apparatus consists of a high speed typewriter, a photocell and a standard radio transmitter.

R.C.A. Direction Finding for American Air Lines. (Aero Digest, Vol. 30, No. 5, May, 1937, p. 64.) (44/48 6050 U.S.A.)

Eight R.C.A. aircraft radio direction finders have been installed by American Airlines, Inc., on their flagship sleepers. This increases the total of radio receivers carried by each sleeper to four:—Long wave beacon, short wave airline, battery operated emergency, and the radio compass. The electro-statically shielded loop of the R.C.A. compass is housed in a small streamlined bakelite nacelle, 24in. long by 9in. diameter, mounted underneath the fuselage. The apparatus is remotely controlled from a control head on the instrument board, and directional reading is given by a left-right visual indicator mounted in a standard round instrument case. For several months past American Airlines have been conducting performance tests on various types of aircraft D.Fs., with a view to selecting the final type for their entire fleet of 54 aeroplanes (and 12 more flagships now on order). In addition to the R.C.A. D.Fs. on the sleepers, the airline also has two Bendix visual D.Fs. on DC-3 Douglas aeroplanes, as well as one radio guide and one aural type D.F. on DC-2s. Tests indicate that the final instruments to be adopted will be of the visual type, and the company intends to make the final decision and outfit the balance of the fleet with aircraft D.Fs. before 1st October, 1937.

Proposed Blind Landing Device (Sorensen). (Aero Digest, Vol. 30, No. 5, May, 1937, p. 64.) (44/49 6051 U.S.A.)

The proposed equipment consists of a number of ultra high frequency receivers (300,000 kc.) which are equally spaced over the landing field, each receiver serving a plot of 1,200ft. square. Each plot is furnished with a relay controlled audio oscillator which radiates its identifying note non-directionally. The oscillator only functions when excited by the landing beam transmitted by the aircraft and which is adjusted to coincide with the normal gliding path. Identifying notes received aboard the aeroplane cause appropriate lights to flash on

an indicating dial. For longitudinal indication, marker beacons are placed on each side of the field and respond to a second beam transmitted vertically downwards by the aircraft. The resulting identifying notes operate the corresponding green and red lights on an indicating dial in the aircraft. Original orientation of the aircraft with respect to the landing area is relegated to the conventional direction finder and the proposed system is intended for the landing only.

Automatic Radio Navigation—French Patent 786,890 *by Radio Navigational Instrument Corporation, U.S.A.* (Revue de l'Armee de l'Air, No. 93, April, 1937, pp. 473-480.) (44/50 6350 U.S.A.)

The object of the invention is to provide an automatic device which—

(1) Gives continuous indication of the direction of an emitting station.
(2) Gives the distance of such a station.
(3) Marks the course of the aircraft or ship on a chart.

The author of the article criticises the apparatus adversely and refers the reader to a better solution, *i.e.*, the Busignies Radio Compass, described in Revue de l'Armee de l'Air, No. 84, July, 1936.

The Hydrocal. A Hydrodynamic Calculating Machine for Solving Unsteady State Problems in Heat Transfer and Other Types of Diffusion. (A. D. Moore, Ind. and Eng. Chem. (Industrial Edn.), Vol. 28, No. 6, June, 1936, pp. 704-708.) (44/51 1691 U.S.A.)

The hydrocal is a hydrodynamic calculating machine for solving unsteady state problems in heat transfer and other diffusion processes. The medium in which the heat flow is to be studied is divided into a number of sections and each is dealt with separately. Water is supplied from a tank to a number of tubes, each one of which represents a sectional element. Small bore flow tubes are arranged to have a resistance to the flow proportional to the known thermal resistance. The volume of water represents the quantity of heat and the height it rises in a standpipe, the rise in temperature. Two models are described, one solving for five sections and the other for 18, and examples of their application are given.

The Contributions of the U.S. Bureau of Mines to Helium Production. (C. W. Seibel, Trans. A.S.M.E., Vol. 59, No. 1, January, 1937, pp. 55-59.) (44/52 4582 U.S.A.)

Investigations into the possibilities of producing helium in commercial quantities were commenced by the U.S. Bureau of Mines in 1917. The source chosen was natural gas from the Petrolia Field of Texas, containing 1 per cent. helium, and the method consisted in liquefaction of all other constituents in the gas by low temperature and pressure. Various air liquefaction processes were tried out, and by November, 1918, the Linde process had produced 200,000 cu. ft. of 93 per cent. helium at a cost of 44 cents per cu. ft. In January, 1929, activities were shut down in the Petrolia Field, owing to anticipated failure of the supply, and the plant moved to Amarillo, Texas. The natural gas here is under a pressure of 700lb. sq. in. and contains $1\frac{3}{4}$ per cent. helium. The plant produces helium of 98.2 per cent. purity and to date has produced 70,000,000 cu. ft. at a net cost of approximately $9 per 1,000 cu. ft. A two-stage process is employed and the final product is obtained at high pressure suitable for direct discharge into tank cars, etc., thus avoiding cost of compression.

Stationary and mobile plants for repurification of helium, which becomes gradually diluted in an airship, have been designed.

Singing Propellers. (H. Hunter, Engineer, 26/2/37 and 5/3/37, pp. 258-260, 285-8.) (44/53 4864 Great Britain.)

Detailed examination of seven bad cases of "noisy" propellers on ships appears to show that whether a propeller is noisy or not is extremely critical. Three factors have to be considered from the point of view of noise production:—(1) The "clapper" or inciting force; (2) the location at which this force acts; (3) the properties of the responding member, in the case of ships, the bronze propeller.

As regards (1) the force is probably due to eddies set up by parts of the hull ahead of the propeller, and can best be reduced by disposing and shaping the hull members so as to avoid eddy formation. A proper shaping of the blades, particularly at the tips, so that they pass through the wake with as little eddy-formation as possible assists in this. As regards (2), it is likely that the inciting forces strike the blade towards the tip, and efforts to reduce eddy-formation should therefore be greatest in this locality. As regards (3) it is possible that the geometrical accuracy of the finished propeller may have to be closer than the usual commercial limits.

Certain physical properties, *e.g.*, modulus of elasticity and elastic hysteresis may have some effect on the responsiveness of the propeller.

The Flow of Metals. (E. N. da C. Andrade, Nature, No. 3,523, 8/5/37, p. 793.) (44/54 6092 Great Britain.)

Prof. Andrade has put forward a theory of liquid viscosity on the basis that the momentum is transmitted, not by the passage of molecules (as in a gas), but by the association of molecules when they touch. On this theory, a formula can be derived for the temperature change of viscosity and for the viscosity at the melting point of a liquid. Molten metals are particularly suited for experiments of this type since they consist of one kind of atom only and are not, in general, associated. The flow of solids is much more troublesome theoretically, but a beginning has been made by the study of single crystals.

Note on the Search for Aeroplanes Lost at Sea. (G. Claude, Compt. Rend., Vol. 204, No. 18, 3rd May, 1937, pp. 1291-4.) (44/55 6199 France.)

The idea of using organic compounds to stain the sea in the region of aeroplane wreckage was tested in January, 1937, by a submarine, by throwing overboard 1 kg. of fluorescin mixed with cork powder in order to spread it over the surface of the water. Solution was so slow that only about one-fifth of the substance, added in the form of the soluble sodium salt, was able to be utilised. An irregular stain, about 200 m. in diameter, was formed, visible to aeroplanes at a distance of 4 km. and lasting for 3½ hours, but most of the colour diffused downwards. Since solutions of fluorescin are rapidly decolourised by the sun it was considered essential that the coloured solution should be formed continuously on the surface. The following process was suggested:—Use of small bamboo cylinders, 10-12 mm. in diameter and 20 mm. in length, each bored with a central hole into which 0.2 gr. of soluble fluorescin is forced between two cotton plugs. A test of this method by a submarine in April, 1937, is described. The stains produced by 10,000 bamboo cylinders (2 kg. of fluorescin) persisted for six hours, and were visible for 1.5-2 km. by a submarine and for 12-15 km. by an aeroplane.

The Italian Height Record. (Les Ailes, No. 831, 20/5/37, p. 7.) (44/56 6267 Italy.)

The French author is of the opinion that the successful record was mainly due to the preliminary engine adjustments carried out in the high altitude chamber and the new type of pressure suit worn by the pilot. This suit was specially designed at Guidonia and consists of a number of garments reinforced both

internally and externally. The helmet is of ample capacity and electrically heated, and it is claimed that the suit is much more comfortable to wear than previous designs. It appears that the engine was practically the standard Piaggio PXI RC 72 (14-cylinder radial, 146 mm. bore and 165 mm. stroke, estimated weight 600 kg., estimated power 1,800 b.h.p.). A specially light fixed pitch four-bladed propeller made of pine wood was fitted.

Aerial Night Camera. (Inter. Avia., No. 428, 1/5/37, p. 5.) (44/57 6332 U.S.A.)

The Fairchild Aerial Camera Corporation has published details of a special aerial night photographic apparatus which for many years has been in use of the U.S. Army Air Corps and which was recently released by the U.S. Army for sale to other governments. The fully automatic camera can be fitted to any aeroplane and will take "snapshots." By pressing a button about 500ft. short of the object to be photographed the pilot releases the flashlight bomb. The greater resistance offered by the parachute to the bomb, than the bomb itself, pulls the ignition tape. The burning fuse causes the bomb to explode in the desired position; the light from the bomb penetrates a light sensitive cell which operates the camera shutter. The camera's present high state of development is the result of experiments over 12 years which hitherto had to be kept secret.

REVIEWS.

RED, WHITE AND SPAIN.
Nigel Tangye. Rich and Cowan. 1937. 7/6 net.

Nigel Tangye likes to see for himself, and in December, 1936, he visited Spain for a few weeks, and toured that part of the country under the control of General Franco. His book is written from the point of view of those who are sympathetic with Franco, as a counterblast to much which has been written on the other side. It is not possible yet to say where the truth lies, for what one sees after the event may not reveal the truth, and the conclusions drawn by two observers of the same events may be entirely different, and both wrong.

Nigel Tangye has speeded through Spain and has picked up odd facts, seen some of the results of a civil war, learnt much, and recorded it in an interesting way. But it will take others, in years to come, to draw more or less correct conclusions of the causes and results of the present trouble in Spain.

The author throws many interesting sidelights on the behaviour of the people during air raids, and of air fighting which will deeply interest all those in aviation.

While in Salamanca he wrote: " Since writing of the raids this morning there have been three more. It is curious that although death generally results from each one of these raids, the populace become used to them as the day proceeds, and only a few take special precautions when the sirens are sounded. This morning the streets were cleared, and when the fifth raid was heralded this afternoon I was walking along the street towards the General Headquarters buildings, and no one took any notice beyond glaring up skywards."

Again: " The war has taught certain lessons. Air power, as such, is not the power it was taken to be. The man with the bayonet is more important than ever in order to follow up and consolidate the striking force of aircraft."

And: " The Italian fighting squadrons are equipped with Fiat biplanes. . . . The Reds have a faster type of machine, and almost all are monoplanes. Although the Italians, in pursuance of their duty of escorting the bombers, have constantly to combat these faster fighters, they do not worry them, as their own biplanes are more manœuvrable and better suited to air combat. This also is of great significance when our own new fighters are considered. Large numbers of very fast, high wing-loaded monoplanes have been ordered for the R.A.F., yet here in Spain pilots, as a result of active service, definitely state that, all things considered, the low wing-loaded biplane is better. Summed up, it can be said that their definite conclusion is that speed is not so essential as the ability to manœuvre quickly."

Sufficient details are given of the types of aircraft being used and fighting tactics to make *Red, White and Spain* a book well worth reading.

METAL AIRCRAFT CONSTRUCTION.
M. Langley. 3rd Edition. Sir Isaac Pitman and Sons, Ltd. 1937. 15/- net.

The third edition of this well-known work by M. Langley has been enlarged and revised and brought up to date. It is one of the most useful books for the aircraft designer which has been published, a statement amply justified by the fact that three editions have been called for in five years.

In this edition a considerable amount of new matter has been added on stressed skin wings and fuselages and retractable undercarriages. Mr. Langley has been able to obtain his examples of metal construction from most of the chief aircraft firms, and the very full details which are usually given of the actual construction and weights are of extreme value. From the wealth of illustrations alone most designers should be able to obtain valuable hints. For the student, as well as for the more experienced designer, " Metal Aircraft Construction " is a mine of useful information which constantly yields a good return the more deeply one digs into it.

INTERPRETIVE HISTORY OF FLIGHT.

M. J. B. Davy, F.R.Ae.S. H.M.S.O. (Board of Education, Science Museum). 1937. 5/- net.

In Captain Davy's name stands three handbooks on Aeronautics in the list of Science Museum publications. These handbooks are models of what handbooks should be, and are mines of information on Heavier-than-air Aircraft, Lighter-than-air Aircraft and the Propulsion of Aircraft (the latter with the assistance of G. Tilghman Richards).

His " Interpretive History of Flight " is intended to " explain the outstanding phases, facts and events in the light of contemporary known development and to provide a coherent narrative." It is divided into three parts: I, The Origin; II, History; III, the Modern Phase.

Part I begins with a study of flight in nature and it is amusing to read that because all creatures that fly are heavier than air this fact has been advanced as an argument against building airships. The author, quite rightly, draws attention to the differing flights of those remarkable birds, the albatross and the gannet, and draws the comparison between the glider and the power-driven aircraft. Stress is laid upon the various forms of flight, especially those of insects, which call for close investigation. The significance of the rigid wing of birds, brought into prominence by Sir George Cayley, is only one aspect of flight and the one which has led to the modern type of aeroplane. But the field of investigation of other forms of flight is extremely large and will, when exposed, undoubtedly lead to new developments at present only vaguely considered. As the author says: " The science of human flight was born in comparatively recent times; it derived nothing from antiquity save the desire to fly." The science is as yet only in its infancy and there is, unfortunately, among scientists, a certain feeling that most of the problems are either sacred or so well on the way to solution that there will soon be little more to learn.

Part II of the History begins with a most interesting chapter on the speculation and the imitation of Nature from early times to the end of the seventeenth century. Here is told the story of the attempt of the Saracen of Constantinople, by artificial wings attached to his body, to imitate the modern flying man, whose stunts thrilled so many before they ended in disaster. The conception and final invention and development of the balloon is considered in the next two chapters. The reviewer cannot help quoting (the book is full of such possible quotations), with reference to early thought on this subject, " An eggshell seems to have provided the best example of a vessel suitable for flotation in the atmosphere, being extremely light, and proposals were even made to fill such shells with water vapour, when, on exposure to solar rays, it was assumed that they would rise in the manner of dew from the grass in early morning!"

From the development of the balloon to that of the dirigible balloon or airship is the subject of the following chapter. The author has the courage to express the definite opinion that the aeroplane is a better vehicle for flight than the airship. The development of mechanical flight and its first successful achievement is dealt with in the chapters which follow and full recognition is given to Sir George Cayley for his clear statements of the principles involved in heavier-

than-air flight, and the practical achievements of Henson and Stringfellow, Lilienthal, Langley, and many others until that final achievement of the Brothers Wright which brought the aeroplane into actual being. The historical section closes with a chapter on the development of the aeroplane in peace and war during the period 1912-1919.

Part III develops the modern phase 1919-1929, the world development of air transport, and the social and economic significance of flight. This last chapter is one of the most interesting and speculative in the book. Here the author makes the most significant statement: "It is becoming increasingly obvious that our knowledge and control of what may be termed the material world—of which the science of mechanical flight is an example—far exceeds that of the mental world, and thus we may easily be stultified by the power we have acquired."

From it the author draws the conclusion that international control of aircraft is not wanted so much as man's control of himself, of more scientific study of his own mind and society. The development of flight has been due to the zeal and inventiveness of many nationalities. "Is it too much to hope that this world wide division of responsibility for the development of human flight may lead collectively to a like sharing of the responsibility for its use?" asks the author.

This is a book which cannot fail to interest even those who feel so surely that they know all about flight, and will not fail to stimulate the thoughtful. Captain Davy is to be congratulated on putting so much into so little space, and in picturing so ably and clearly the task he set out to do, to interpret the history of flight. It is a book which should be widely read.

A Simple Study of Flight.

J. D. Haddon, B.Sc., A.F.R.Ae.S. Sir Isaac Pitman and Sons, Ltd. 1937. 3/6 net.

This is a book which supplies the missing link between the very elementary and the more advanced mathematical books on the theory of flight. Captain Haddon has had a wide experience of teaching aeronautics, and his two books on Structures, and Properties and Strength of Materials are well known.

The book begins with a chapter on air resistance in which is explained simply and clearly such terms as eddying motion, streamline flow, skin friction, scale effect and Reynolds number. Chapter II on aerofoils shows the meaning of lift and drag coefficients and their importance, centre of pressure, etc. A footnote explains that the symbols $\frac{1}{2} C_L$ and $\frac{1}{2} C_D$ have been adopted instead of K_L and K_D, and in the next edition it is hoped that these symbols will be adopted in that text. In Chapter III the forces on the complete aeroplane are clearly and simply explained in normal flight and simple manœuvres. The next chapter on controls naturally follows and there is a final chapter on stability.

Captain Haddon not only writes well, but he illustrates much of what he says by many excellent and useful examples in his text. A simple study of flight is, indeed, a most useful introduction to anyone who intends to make a serious study of flight problems and will lead him by easy straight paths to the wider but perhaps more winding roads which he will ultimately have to follow.

Air Transportation Costing.

Captain N. T. Macleod, M.C., D.C.M. Sir Isaac Pitman and Sons, Ltd. 1937. 7/6 net.

Captain N. T. Macleod is the cost accountant for Canadian Airways, Limited. The book is a guide to an arrangement of the different items of air transportation operating expenditure, so that the costs of operation for any type of aircraft over any scheduled route may be determined.

There is yet a considerable amount of spade work to be done on air transport and the finality of costing, as obtained by the railways, will not come for some

time yet. Many factors in air transport are not only not yet stable, but many are forced to change with the seasons. For example, in Canada an aircraft may be called upon to operate on floats during the summer months and on skis during the winter months, giving an entirely different cost for the same aircraft operating on wheels throughout the year.

The book under review contains many sample tables of costs and suggested flight report sheets and other data sheets, which will form a basis for the final costing reports. For all those concerned in air transport this is a book to read and digest.

JAHRBUCH 1936 DER LILIENTHAL-GESELLSCHAFT FUER LUFTFAHRT-FORSCHUNG. Muenchen und Berlin, published by R. Oldenbourg. 646 pages. Price R.M. 20.

The Lilienthal Society for Aeronautical Research, an official German institution created during the last year, publishes in its first year book valuable scientific and technical information in the form of rather short abstracts taken from 62 papers dealt with by the society.

An especially interesting theoretical experimental study refers to the airflow in the slipstream (by F. Weinig), another (by I. Lotz) to the lift distribution influenced by the slipstream showing the suitability of Koning's simplified theory.

The aerodynamical improvement of a Junkers Ju. 86 monoplane wing is described in detail (by A. W. Quick). The original wing with swept back leading edge and a taper ratio of 3.7 showed a poor rolling stability near the stall. A modified wing with a different shape, pronounced wash-out and an altered division of the well-known " double wing " flaps resulted in a marked improvement, the calculated lift distribution near the stall being well in agreement with wind tunnel tests and full-scale observations. At the stall the plane becomes nose heavy with flaps full on, without any tendency to drop a wing, the burbling starting from the wing roots.

Lateral stability tests done by the D.V.L. research institute (F. Wenk), by measuring free oscillations in flight after the application of an initial disturbance, seem to be much simpler than and as conclusive as the general method (additional definite moment about longitudinal and vertical axis under stationary flying conditions). The modern theory formulated by Mathias is well in agreement with the results of the D.V.L. tests, and seems to be sufficient even for the more general study of the problems of servo pilot control.

A. Lippisch investigates the influence of aileron shape with the help of known methods for the calculation of lift distribution along the span. Wings of different taper give the optimum of rolling moment for a given aileron area (10 per cent.) with an aileron span of 80 per cent. of the semi-span. Ailerons with short span and a great chord are poor with regard to both the rolling and the yawing moment. Skewed ailerons are only slightly inferior and promise an improvement in inherent stability. The results obtained are well in agreement with American tests (N.A.C.A. Rep. No. 419).

Investigations with wing oscillations and the influence of aileron damping are discussed by several authors.

The static part is concerned with a study of factors of safety, with progress with rolled aluminium alloys, with methods for measuring strains in finished parts, especially internal strains (due to welding and heat treatment), " season cracking " and effect of resilient strains (certain alloys appear to be unsuitable only for this reason), intercrystalline corrosion set up under strain (duralumin being inferior to Alclad and magnesium alloys), notch strength tests on steels and endurance loading tests with bolts (the results obtained explaining ruptures occurring under lower than the specified load due to the notch effect of the thread accompanied by a detrimental " normal " heat treatment after cutting the thread).

The importance of " shape strength " in the design is highly stressed (the value of strength depending only upon the shape and independent of the material).

That is emphasised in a very remarkable research report dealing with engine crankshafts (K. Luerenbaum). The actual shape strength of normal aero engine crankshafts under working conditions is only a small fraction of the static strength of the material (less than 1/11th for torsional stresses, the " scale effect " included). These low final strength values have been well established during endurance tests made by the D.V.L. institute with normal full size crankshafts. Modified shapes designed with a careful consideration of a very gradual transition of forces allow for a higher strength (an increase of 37 per cent.), but impose an expensive construction. It seems that the usual crankshaft steels of high static strength, but poor dynamic strength qualities (low notch strength and poor damping capability under sustained vibrations), could be better and more economically replaced by cast iron, which proved to be superior under dynamical loads. The results of endurance tests with a cast iron crankshaft of a Ford car confirm this view.

Aluminium alloys as a material for engine bearings could be promising because of their low friction under high loads and speeds, but are rather sensitive against impurities in the lubricating oil and will not stand dry running well.

Tests by the D.V.L. institute with all kinds of bearing materials (including bakelite) show soft metals with high compression strength and no brittleness under hammering to be preferable. Otherwise, crankpin bearings made of aluminium alloy have been tested in a Junkers' compression ignition engine with success.

The torsion of thin-walled cylindrical shells with stiffeners is treated by E. Schapitz. Experiments show that Donnell's formula for the buckling moment still holds fairly good, but that it cannot be regarded as generally valid. A modified formula of Wagner-Ballenstedt, taking into account certain assumptions about the formation of buckling waves, seems promising. Optical procedures using transparent models in polarised light for the measurement of strain are especially considered for the study of stressed skin construction.

Tests with new adhesive materials made by the D.V.L. institute (P. Riechers) included Kaurit glue and a hitherto not used species of artificial resin (Polyvinyl, " P "-folie) for dry glueing. Ply built up with P-folie shows higher strength and an excellent bending quality. This result led to preliminary experiments with pressing out rather complicated bent parts out of the new ply after boiling the ply for a few minutes. According to these experiments it seems to be possible to stamp parts out of treated ply similar to metal sheet parts without destruction of the fibre, perhaps a promising way to rational wooden aircraft construction.

Research work for metal sailplanes, conducted by the Deutsches Forschungs-Institut fuer Segelflug (L. Roth), resulted in a fairly simple kind of riveted light alloy construction using only about 12 standard sections. Parts made accordingly proved under test well as regards weight and strength, and seem to allow for " home construction " by means of special hand operated riveting apparatus. The weight of certain parts for gliders went down to 42 per cent. of the weight of the correspondent part constructed in wood. Even the problem of easy repair seems to be solved. One definite advantage is certainly the training of workmen in modern light metal construction. For real sailplanes, the all-metal construction appears to be somewhat more troublesome, because investigations show that duralumin wing noses (0.2 mm. thick, much less than 30 S.W.G.) behave under torsional stress inferior to plywood ones. The metal wing of a strut braced two-spar training glider of 38ft. span resulted in a specific wing structure weight of 0.47lbs./sq. ft. for an ultimate load factor of about 9.

D.V.L. tests with landings on skids proved that up to a wing loading of 10.3lbs./sq. ft., no difficulties are to be expected.

With regard to engine starters the experience of the Deutsche Luft Hansa shows that difficulties still exist in cold weather. Starting with compressed air becomes obsolete (except for compression ignition engines), because of its incon-

venience and of the harm done to the engine; 80 per cent. of all engines used by Luft Hansa are radials and all of them are now fitted with electric inertia starters (Eclipse license). At low temperatures it is necessary to preheat the whole engine (including the lubricating oil). A special hot air preheater designed by Luft Hansa and burning petrol saves time and petrol expenses for warming up by running the engine on the ground. This D.L.H. preheater is sufficient for the heating of three engines at the same time. Electric preheaters for water and oil installed in transport planes are under service test.

Further reports worth while mentioning include:—Investigations concerning wind forces and seaway, sea wave measurements, aero photography and photogrammetry, wireless direction finding by the impulse method, navigational requirements, magnetic controlled compasses with direct or distant reading, the new Anschuetz twin gyro " space " compass (a combination of gyroscopic compass and artificial horizon for aircraft, promising to be useful not only for navigational purposes but also for automatic control and for the armament), experience with the construction of modern aerodromes, aerodrome illumination, aeromedical research (especially the chemistry of breathing, the voluntary hyperventilation being found to result eventually in an early breakdown during altitude flight, due to impoverishment of CO_2 of the body).

The 617th Lecture to be read before the Royal Aeronautical Society since its foundation on January 12th, 1866.

PROCEEDINGS.

A meeting of the Royal Aeronautical Society was held in the lecture theatre of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2, on Thursday, February 18th, 1937, when a paper on "Trend of Air-Cooled Aero Engines—the Next Five Years," by Mr. A. H. R. Fedden, was read and discussed. In the chair, Mr. H. E. Wimperis.

The PRESIDENT: The introduction of anyone so well-known as Mr. Fedden to an audience of the Royal Aeronautical Society was quite unnecessary. It was clear that the development of aero engines in the future would become more and more intensive, not only in quantity, but also in quality, and that designers would have a difficult task in steering the right course between the obstacles and difficulties in design on the right hand and the left. It was also becoming clear that in respect of both the aero engine and the aeroplane a very much higher degree of intelligence in design was being called for. So that any great power which was to be equipped with an air arm needed a combination of great gallantry on the part of the user and fine intelligence on the part of the designer. Though gallantry and fine intelligence were not the very highest of human qualities, they were nevertheless very excellent qualities, and it was only by the aid of a combination of them that the material leadership of the world could be gained in the future. That was perhaps consoling, especially in view of the fears which were so commonly expressed as to what the future might hold in store for us. The President added that there could be no better representative of the quality of fine intelligence than Mr. Fedden.

TREND OF AIR-COOLED AERO ENGINES—THE NEXT FIVE YEARS.

By A. H. R. FEDDEN, M.B.E., M.I.A.E., M.S.A.E., F.R.Ae.S.

(1) GENERAL INTRODUCTION.

In July, 1935, I had the honour of reading a paper before a joint conference of the Royal Aeronautical Society and the Society of British Aircraft Constructors, entitled, "Future Research on Air-Cooled Aero Engines." Much water has flowed under the bridges since that date, and we have entered on a period of intensive activity and development in aeronautical matters not fully envisaged 18 months ago.

A number of the suggestions put forward in my previous paper, as being suitable subject matter for research or investigation, have been, or are in course of being, investigated by various Government departments, or interested firms in this country, so that, when I received an invitation from the Royal Aeronautical Society to read another paper during the present Session, I thought it might prove useful to endeavour to write an addendum to the original paper, and try to outline the trend of a future air-cooled power plant for aircraft which would be built during the next five years, it being presumed that these engines

would be designed as a result of the experimental work which had already been completed, or is being carried out at the present time, and with the object of meeting the more searching requirements demanded by this increased activity.

It is not claimed that this paper is a highly technical commentary, or a definite, prescribed programme of what the immediate future may hold out for air-cooled aero engines, but rather it is intended to put forward "feelers," in a logical and commonsense way, of what may reasonably be accomplished within the time under review, with the idea of promoting a discussion on the subject.

It is appreciated that any such review must be purely an estimate, based on conclusions drawn from a set of assumptions leavened by the results of current research work. Such an opinion is certainly open to any amount of conjecture and criticism, but the very fact that at least four years are necessary to develop an entirely new type aero engine from its original conception, through its teething troubles, to the production stage, would seem sufficient justification for such a review, and to be a subject of paramount importance, and worthy of attention and discussion on the broadest possible basis.

Moreover, there are certain other aspects of recent aircraft development which make the task of the right selection of type, by the air-cooled aero engine designer, a matter of greater importance than ever before. A considerable step up in performance, generally, and a greater cleanliness of design, of all categories of aircraft, have given rise to the necessity for "horses for courses" in the form of specialised engines. The day of the general purpose engine, except for certain civil aircraft requirements, is fast disappearing.

Some years ago aircraft power plant could be successfully developed without a very close touch or intimate knowledge of the trend of aircraft requirements, but little hope of success can be held out for such a procedure to-day. Previously it was the custom to produce a design of engine from which it was planned to obtain smallish orders for engining aircraft of widely diversified types, and for which it was hoped to build up a sufficient production to justify adequate tooling for fabricated quantity production. Similarly, engines were launched into production on a comparatively low horse-power rating, with the avowed intention of stepping up output as the necessity arose. I suggest that such a policy is a great deal more difficult to-day and, in my opinion, will be impossible in the future.

The improvements in fuels, and the more exacting requirements of aircraft, demand a full-blooded series from the inception of the type. The hope of reward, if entirely successful, is greater than in the past, but the line of demarcation between accomplishment and failure is a narrower one.

It is believed that with the march of progress, and as the development and bringing to fruition of an aeroplane engine becomes a more and more expensive and prolonged undertaking, which, in my opinion, is inevitable, it will be impracticable to make changes in design as rapidly as in the past, and, having chosen a type and carried it through to the production stage, it may have to remain unaltered over a longer period than has been normal practice in the past. These trends emphasise the vital necessity of a wise choice when a new design of engine is in the project stage, and the importance of adequately weighing it up from all angles, and of spending as much time as possible on its analysis on the drawing board before deciding to transfer it to the flesh.

Assuming these assumptions are correct, I believe the aircraft designer may hope for a more specialised and highly developed product in the future, but he may have to be content to make use of a given type of engine for a longer period with comparatively little or no development, unless competition is so severe that more rapid changes are made feasible. It is believed that the cost of development of the modern high efficiency aero engine is not very likely to enable this to come about.

This short introduction is intended to serve as the *raison d'être* of this paper, which it is hoped will provide a useful discussion, and act as a guide to the engine designer as to the trend of air-cooled aero engines for the next five years.

(2) Types of Aircraft for which Engines are Required.

Before attempting to analyse the layouts of new air-cooled power plant, it would seem advisable to endeavour to envisage the most important types of aircraft for which these engines are required, and approximately the speed and range that may be expected from them.

I realise that to attempt such a task may appear extremely rash, especially when the information emanates from the power plant camp, but, if I am correct in my introductory remarks, this new vintage of engines is crying out for some such review, and without it the task of the engine designer is a very difficult one. Several examples have been seen, of recent years, of perfectly good aero engines having been designed and made, which fill no useful field owing to the engine designer having an incorrect original conception.

I would like to say that these projected categories and speeds of aircraft are deduced entirely on my own responsibility, as the result of general observation, and may be thought to be too conservative, but I cannot but believe that the marked stepping up in performance, of different types of aircraft during the last few years, must level out and gradually slow up, and will inevitably result in a somewhat longer period for new development; that we must expect an eventual flattening out of the curve, and that, in spite of certain views to the contrary, no very drastic changes in layout of aircraft will be made during the period under review.

In 1933 there arrived the classic Douglas type, which was in effect a very sane and logical development, consisting of a clean, low wing monoplane of comparatively high wing loading, stressed skin structure, and with retractable undercarriage, and cowled radial engines fitted with controllable pitch airscrews, and mounted on the leading edge of the wing. For the purpose of this paper it is assumed that, basically, this type will be continued for some considerable period in variant forms, in larger sizes, and with a greater number of engines, and also in smaller forms—twin engines gradually replacing single-engined machines for all purposes.

It is considered that recent estimates of the possible performance of aircraft in the immediate future have, in certain instances, reached figures which it is by no means certain are in the best interests of aviation. It is suggested that a wiser mental attitude would recognise that there are natural limits to progress at any given stage of development, but would also refuse to regard these limits as immutable and rigid barriers. Development can then be defined as the art of raising the limit of what is possible.

If this conjecture is correct, the larger types of aircraft will most probably continue to use engines mounted in one plane in-line on the leading edge of the wing, in arrangements of four, six, or eight, according to the size of the machine.

A point worth noting in connection with the mounting of a number of engines on the leading edge of the wing is that, for the higher powered categories, in order to obtain the necessary thrust for take-off, a low reduction gear to the engine, and a larger diameter propeller, will be necessary. This means that the engines will have to be comparatively widely spaced. The necessary clearance for propellers of 1,500 to 2,000 horse-power, with 0.35 to 0.38 reduction gear ratios, may produce quite a serious problem, so far reaching and fundamental that it may actually affect engine design to the extent of a larger number of units being chosen for a given total of horse-power by the aeroplane designer, or, alternatively, two-speed gears in conjunction with controllable pitch

propellers, or double concentric propellers. It would be most helpful to hear aircraft designers' views on this subject because it so fundamentally affects engine layout.

It is understood that aircraft designers are awaiting the results of some important research work affecting wing sections and their characteristics which may have a far reaching effect on engine design, and which is in course of being investigated at the present time. It is also understood that wing loadings of 30 to 40lbs. may be expected, and speeds in excess of 400 miles per hour may be envisaged without coming into the danger zone of the compressibility burble.

However aerodynamically clean aircraft may become in the near future, speeds of this order mean a good deal of horse-power; and a considerable step up in unit size of engines, as compared with that which we are accustomed to to-day, must be contemplated.

Although flying at a considerable altitude reduces the specific output required from the power plant for a given speed, it does not seem possible that stratospheric flying will be current practice within the period under review, except for a few special purpose military squadrons, and possibly for experimental civil aircraft. The trend of propeller and aircraft design seems to indicate that, at any rate for this stage of development, the engine designer will not have to provide for groups of engines geared to a single propeller, and that single-engined units, combined with the normal type propeller, will be more acceptable.

As a basis for discussion, therefore, it is suggested that the main aircraft categories may be divided up as shown below:—

PROBABLE MAIN AIRCRAFT CATEGORIES.

Type	Maximum Speed. m.p.h.	Cruising Speed. m.p.h.	Cruising Range.
Civil			
Land Machines ...	275	220	1000-1500 miles
Seaplanes	250	200	1500-2000 ,,
Special Category			
Long Range Machines	250	220	3000-4000 ,,
Military			
Destroyers	425-450	—	1½-2 hours.
Multi Place Fighters	400	—	1½-2 ,,
Medium Bombers ...		300	6 ,,
Heavy Bombers ...		275	8 ,,
Seaplanes	270	220	10 ,,

(3) ENGINE CATEGORIES TO MEET NEW AIRCRAFT DEMANDS.

Assuming that the types suggested in section (2) cover the main requirements of civil and military aircraft for five years ahead, I propose in this section to suggest the sizes and weights of engines to cover this range of aircraft.

It is not intended to attempt to cater for the smaller civil categories—sports, private, training, or feeder types—not because I think that these are unimportant or uninteresting groups, but because it is considered that they are quite a separate section which should be dealt with apart from the large civil and military types of aircraft.

As I have already suggested in this paper, I am of the opinion that the new vintage of engines will require more time and money spent on their development than previously, and it is, therefore, more important to try to keep down the

number of types as far as possible, and I hope to be able to cover the suggested range of aircraft by four sizes of engines, as shown below:—

750 h.p. for 820lbs.
1,150 h.p. for 1,250lbs.
1,550 h.p. for 1,550lbs.
2,000 h.p. for 2,100lbs.

These weight figures include standard equipment as per Air Ministry Instruction E.124, issue 3.

(4) FUEL.

In section (3) of my previous paper, I suggested a list of the most important subjects for research as affecting the future development of air-cooled aero engines, and placed fuel first and foremost, believing that this was the most important item, and I endeavoured to deal with this matter at some considerable length 18 months ago. It is proposed to refer to this matter again, as I feel that it is still the all-important governing factor. Actually the position in regard to the supplies of 100 octane fuel seems a good deal more hopeful than it was 18 months ago. During the period under review, it is understood that there is little doubt that we shall have 100 octane fuel as readily as we have 87 octane to-day, and it is possible that we may have even better fuel than 100 octane. I gather that the supplies will probably be in the form of iso-octane, and it may be quite likely that it will be ready in quantities before the engine makers have developed their new engines to make full use of it.

From this fuel, in properly designed engines, I think we may expect an increase in horse-power of 25 per cent., with a decrease in consumption of 5 to 7 per cent. This should enable a consistent cruising consumption of 0.42 pints per brake horse-power hour, at approximately 60 per cent. of the maximum power rating.

These improvements in fuel for electric ignition engines will make the case for the compression ignition engine system even more difficult to substantiate than before. It will make the compression ignition engine less valuable from a consumption point of view, from the aspect of the volume of fuel consumed, but the price of the fuel will still be considerably in favour of the compression ignition type of engine.

Events of the last few years have given the petrol aero engine an enormous advantage over its only competitor, and although, at any rate for the next few years, I am afraid the requirements of military over civil aero engines are likely to be in the ratio of at least 8 to 1, which, on the face of it, would appear to retard further the advent of the successful compression ignition engine, nevertheless the advantages of the greatly minimised fire risk, cheapness of fuel, elimination of radio interference problems, and the general higher order of reliability that should ensue from the compression ignition type of engine, are important factors which cannot be overlooked.

Personally, I lean to the view that for long range night bombers of moderate performance, as well as civil aircraft, there is a great deal to be said for the compression ignition engine in fairly large sizes and of not less than 1,000 cruising horse-power. It is impossible, however, to take such a high specific output, from a given swept volume, from the compression ignition engine, as from the corresponding petrol engine, but it is practicable to take a higher percentage cruising output, from a given size, from the compression ignition engine, and, if we are to look to mechanically assisted or catapulted aircraft for the future, then the compression ignition engine has a better chance of coming into its own.

I have looked into the possibilities of the compression ignition engine as compared with the petrol engine, on a comparative basis, for a thousand cruising horse-power, and the main features of each type are shown in the following table:—

COMPARISON OF 1,500 B.H.P. AIR-COOLED RADIAL ENGINES—100 OCTANE AND COMPRESSION IGNITION.

		100 Octane Petrol Engine.	Compression-Ignition Engine.
Horse power at maximum R.P.M. and Rated altitude (5,000 ft.)		1500	1500
Cruising B.H.P. at 66 per cent. max. power		1000	1000
Cruising Consumption	Lbs./b.h.p./hour	0.435	0.38
	Pints/b.h.p./hour	0.47	0.36
	Gallons/hour	59.0	45.0
Nett. dry weight—lbs.		1620	2100
Weight per B.H.P.—lbs.		1.08	1.4
Fuel cost per hour basic prices— 100 octane— 2/6 per gallon Fuel oil— 1/2 per gallon	(a) No transport charge	£7 7 6	£2 12 6
	(b) 1s. 6d. per gallon transport charge	£11 16 0	£6 0 0
	(c) 2s. 6d. per gallon transport charge	£14 15 0	£8 5 0
Saving in fuel cost per hour	(a) No transport charge		£4 15 0
	(b) 1s. 6d. per gallon transport charge		£5 16 0
	(c) 2s. 6d. per gallon transport charge		£6 10 0

It will be noted that the lower specific fuel consumption of the compression ignition engine results in a total consumption per hour of 45 gallons, as against 59 gallons for the 100 octane engine, at similar cruising power, and an incidental, but none the less important advantage of the reduced consumption of the compression ignition engine is the economy to be effected in weight and size of tanks.

In an endeavour to demonstrate the economies in fuel charges to be expected from the compression ignition engine, I have shown figures for the fuel cost per hour cruising for the two engines under consideration. It has been assumed that the basic cost of 100 octane fuel, without transport charges, would be 2s. 6d. per gallon, and, for fuel oil, 1s. 2d. per gallon. These figures are, of course, purely arbitrary and must be taken solely as my own opinion as to what the relative costs may be in the next five years. In deciding on these relative costs, I do not think the compression ignition engine has been favoured at all. Three cases have been taken for relative cost—(a) with no transport charge, (b) assuming 1s. 6d. per gallon transport charge, and (c) assuming 2s. 6d. per gallon transport charge, with a view to representing probable costs in undeveloped countries where the transport of fuel becomes exceedingly expensive.

If we consider the case of two 4-engined machines of 72,000 lbs. all up weight, and a power loading of 12 lbs./horse power, one having 100 octane petrol engines and the other having compression ignition engines, each with the characteristics as outlined on the previous slide, then, of the two graphs, Fig. 1, graph (A) indicates the payload for a given flying time under cruising conditions. From this curve it will be seen that the compression ignition engine is at a disadvantage for flying times below 9½ hours, at which point the payload is approximately 14,500 lbs. representing 20 per cent. of the all up weight. At the Atlantic range of 2500 miles, against a 40 miles per hour head wind, it will be seen that the payload is 1500 lbs. greater with the compression ignition engine.

Graph (*B*) is derived from graph (*A*), and indicates the effect on range for a given payload, when using compression ignition engines in place of 100 octane petrol engines.

The vertical line on this curve is drawn at the point where the payload is equal to that for the aircraft with 100 octane engines equipped for the Atlantic range,

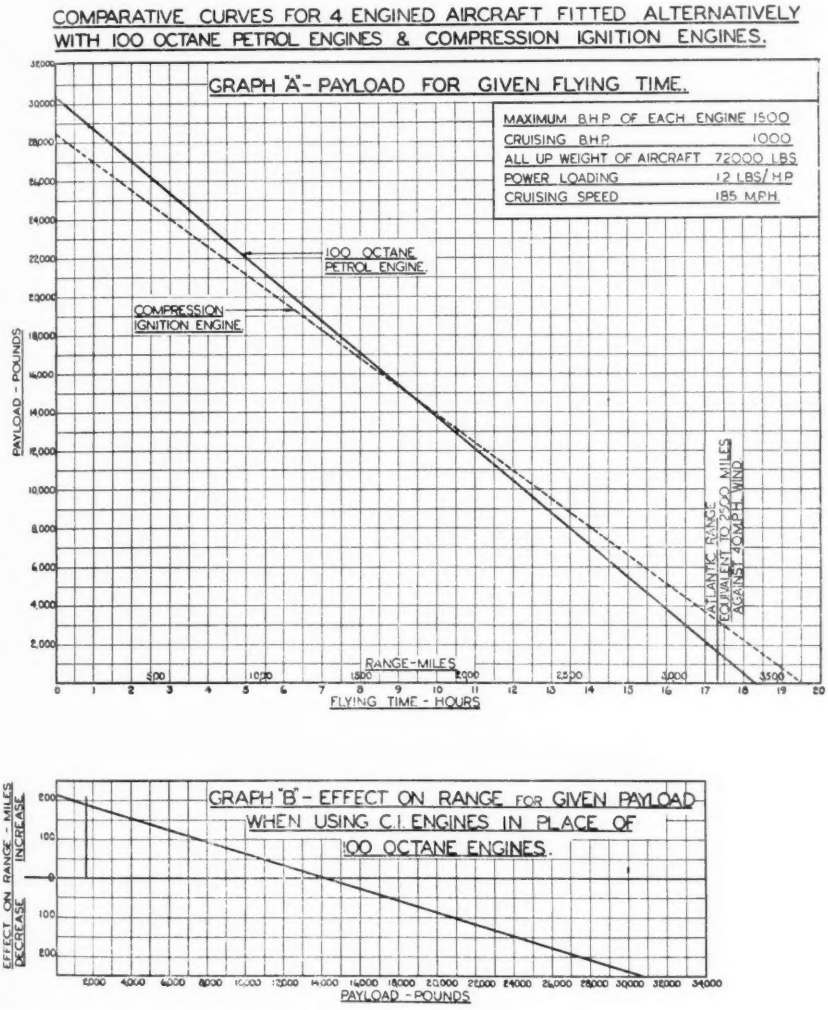

COMPARATIVE CURVES FOR 4 ENGINED AIRCRAFT FITTED ALTERNATIVELY WITH 100 OCTANE PETROL ENGINES & COMPRESSION IGNITION ENGINES.
GRAPH "A" - PAYLOAD FOR GIVEN FLYING TIME.
MAXIMUM B.H.P. OF EACH ENGINE 1500
CRUISING B.H.P. 1000
ALL UP WEIGHT OF AIRCRAFT 72000 LBS
POWER LOADING 12 LBS/H.P.
CRUISING SPEED 185 M.P.H.
100 OCTANE PETROL ENGINE.
COMPRESSION IGNITION ENGINE.
ATLANTIC RANGE EQUIVALENT TO 2500 MILES AGAINST 40 M.P.H. WIND
PAYLOAD - POUNDS
RANGE-MILES
FLYING TIME - HOURS
GRAPH "B" - EFFECT ON RANGE FOR GIVEN PAYLOAD WHEN USING C.I. ENGINES IN PLACE OF 100 OCTANE ENGINES.
EFFECT ON RANGE - MILES INCREASE DECREASE
PAYLOAD - POUNDS

FIG. 1.

and it will be seen that, for a similar payload, the compression ignition engine would give an increased range of 190 miles.

It is interesting to note the enthusiasm and activity shown towards the production of the compression ignition aero engine on the Continent, and to speculate on the reasons for this interest.

I can raise no enthusiasm for the theory of a ray to cut out the magneto of a spark ignition engine, nor foresee any real difficulty in producing considerable quantities of petrol of a reasonably high octane value.

There is no doubt in my mind that there is a considerably decreased fire risk when employing compression ignition engines in aircraft, especially when compared with 100 octane engines where much closer cowling and higher specific output will increase the chance of fire if the engines are running at the time of a forced landing, because everything inside the cowling will be considerably hotter, than was the case in the earlier type of petrol engine installation. Fire risk as the result of a crash of an aircraft cannot be considered of real military importance, but it is interesting to speculate on the respective chances of aircraft being set alight while in the air, when powered alternatively with a petrol or heavy oil engine.

I much deplore the fact that greater energy is not being applied to the problem of the compression ignition engine for aircraft in this country. In the past official support has been given to compression ignition research, and the Bristol Company, amongst others, have undertaken a considerable amount of experimental work along these lines, but unfortunately the progress of the petrol engine has been so rapid that up to the present it has not been deemed advisable to carry these efforts beyond the embryo stage.

I believe my estimates for the compression ignition engine are conservative, and, assuming these figures are correct, it would be interesting to know, from aircraft designers, what is considered to be the value of such a type of engine.

In my opinion, the psychological moment has now arrived for such a proposition to be tackled quickly, and on a high priority, at any rate for the third suggested category of power plant, and I submit that it warrants sufficient money being set aside for its development, and the best brains in the country being concentrated on it.

(5) Engine Layouts from the Geometric Aspect.

In this section it is proposed to discuss some of the most important items governing the geometric layout of air-cooled power plant.

Many factors contribute to the design and form that air-cooled aero engines may take, included in which are power, prime cost, weight, balance, firing order, distribution, fuel consumption, accessibility, and maintenance; all play their part and cover, what I shall term for the purpose of this paper, the geometric layout. Cooling drag, and bulk or wetted surface, I shall term the aerodynamic layout, and this is dealt with in the next section.

I had hoped to be able to produce a figure of merit for the various types of aero engines at the last Paris Salon, but, after due deliberation, I have been persuaded that this is not feasible; so many factors have to be brought into such a formula that it would become impracticable.

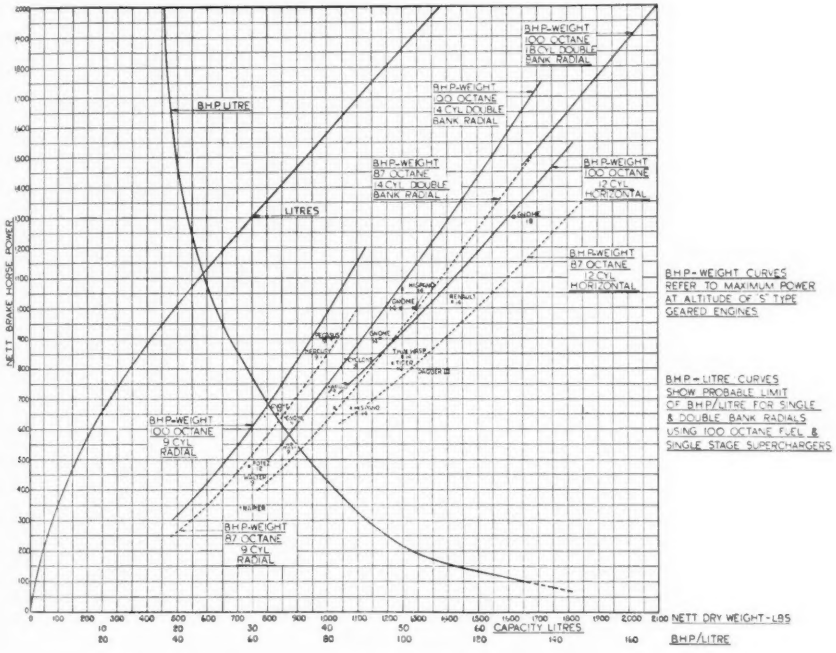
Before proceeding to talk of the future, it may be instructive to look back on the past, and the table shows the state of affairs at the last three Paris Salons.

Paris Salon 1932-34-36.

Analysis of Air-Cooled Engine Exhibits over 500 b.h.p.

	1932	1934	1936
Air cooling	42%	50%	69%
Layouts			
Radial	100%	95%	95%
Other types	—	5%	5%
Ratings			
500-750 b.h.p.	89%	69%	45%
750-1,000 b.h.p.	11%	26%	33%
1,000-1,300 b.h.p.	—	5%	22%

Although this tabulation is interesting, and there are some lessons to be learnt from it, it cannot be taken too literally, but merely as a guide as to the trend for the future. As mentioned in section 4, the small sizes of engines are omitted from this tabulation. This chart shows a steady increase in the percentage of air-cooled engines, and that the radial air-cooled engine is holding its own. It is interesting to note that the percentage of engines between 500 horse power and 750 horse power has decreased, whilst an increase is shown in the 750 horse power to 1000 horse power, and the 1000 horse power to 1300 horse power classes. This is, to some extent, due to the development of existing types, and to the use of better fuels. It also serves to demonstrate the general tendency for increased power. It is pointed out that the figures for the 1936 Paris Salon are bound to


B.H.P.-WEIGHT 100 OCTANE 18 CYL. DOUBLE BANK RADIAL
B.H.P.-WEIGHT 100 OCTANE 14 CYL. DOUBLE BANK RADIAL
B.H.P.-WEIGHT 87 OCTANE 14 CYL. DOUBLE BANK RADIAL
B.H.P.-WEIGHT 100 OCTANE 12 CYL. HORIZONTAL
B.H.P.-WEIGHT 87 OCTANE 12 CYL. HORIZONTAL
B.H.P.-WEIGHT 100 OCTANE 9 CYL. RADIAL
B.H.P.-WEIGHT 87 OCTANE 9 CYL. RADIAL
B.H.P./LITRE
LITRES
NETT BRAKE HORSE POWER
B.H.P.-WEIGHT CURVES REFER TO MAXIMUM POWER AT ALTITUDE OF 5' TYPE GEARED ENGINES
B.H.P.-LITRE CURVES SHOW PROBABLE LIMIT OF B.H.P./LITRE FOR SINGLE & DOUBLE BANK RADIALS USING 100 OCTANE FUEL & SINGLE STAGE SUPERCHARGERS
NETT DRY WEIGHT-LBS
CAPACITY LITRES
B.H.P./LITRE

CURVES SHOWING WEIGHT-B.H.P. LITRES-B.H.P. & B.H.P./LITRE FOR VARIOUS TYPES OF AIR-COOLED ENGINES.

FIG. 2.

be somewhat incomplete, owing to the absence of German and Italian exhibitors.

Power is obviously dependent upon the required performance of the aircraft, and, in the present state of the art, it would appear that to employ cylinders of more than $5\frac{3}{4}$in. to 6in. bore introduces very serious problems, and it will therefore be appreciated that, when we approach the higher categories of power, viz.: 2000 horse power, it is difficult to find a geometric layout, even with the largest size of cylinder, that will give us the required power, and still remain a reasonably simple production proposition.

We will consider the question of cost, ease of production, and weight, together, as all of these may be conveniently grouped. Low first cost, ease of production, speed of removal and re-installation, are all agreed to be important to the Civil Air Line Operator, but it is felt that comparatively little attention is at present

paid to them for military purposes. The present Air Ministry Expansion Scheme has emphasised the vital necessity for due consideration being given to such problems. There is little doubt that ease of production of a straightforward design, by relatively unskilled labour, is a factor which must be regarded with due importance, and that aircraft constructors must be encouraged to give the fullest consideration to those types at the expense of others which are more difficult and expensive to produce, unless the latter offer very considerable advantages from the aspect of performance. Fewness of parts, light weight, and symmetrical layout, certainly contribute towards low cost and ease of production.

On general principles, therefore, the greater the number of cylinders per unit volume, the greater the weight; and the smaller the volume of engine, the higher the specific output of horse power that may be expected. These claims are illustrated graphically on Fig. 2, which provides a composite series of graphs taken from plottings of a number of different engines, and illustrates the lightest practical form of engine for any given horse power, and the effect of cylinder capacity and total volume on specific output.

The series of short curves compare weight and horse power for different types of engines, the dotted lines being for 87 octane fuel, and the full lines for 100 octane fuel. It will be noted that the 100 octane 9-cylinder engine is the lightest type of engine, and, in this case, it has been carried up as far as 1200 horse power to illustrate the argument. The dotted line shows the 87 octane 9-cylinder carried up to 1000 horse power. The 14-cylinder double bank radial—87 octane with dotted line, and 100 octane with full line—is the next lightest series shown, and powers are carried up to 1500 and 1750 horse power respectively.

The flat 12-cylinder 87 octane engine will be seen to be heavy, and is shown carried up to 1350 horse power. The flat 12-cylinder 100 octane engine is a good deal better, and is shown carried up to 1550 horse power.

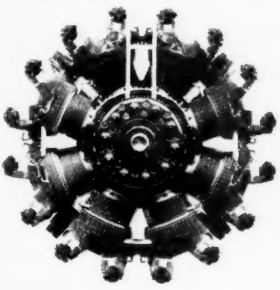
As regards the in-line multi-bank engine, I have only attempted to deal with the 12-cylinder flat in-line engine in this group of curves, because such engines as the 24-cylinder " Cross " type, in the higher powers, would be even less favourable in regard to weight per brake horse power.

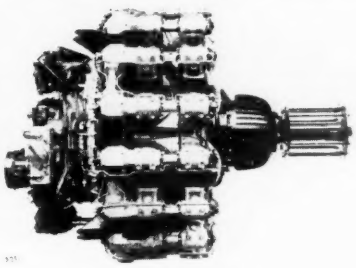
The last curve of the group shows the weight advantages of the radial in the higher powered categories.

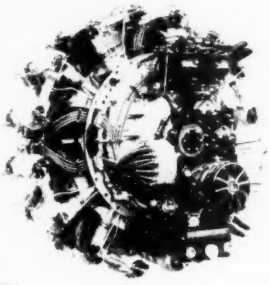
Turning now to the two large curves, and starting with the one in the bottom right hand corner, comparing brake horse power to brake horse power per litre, it will be seen that, with the quite small engine of less than 100 horse power (and for the purpose of this curve the examples are not, of course, aero engines, but special racing motor car and motor bicycle engines), the output goes up as high as 140 to 150 horse power per litre. As the total power of the engine is increased, so the output per litre goes down, until, for a 2000 horse power engine, it has dropped to 37. Turning to the other curves, starting at the left hand bottom corner, dealing with brake horse power measured against litre capacity, it will be seen that, whereas 1000 horse power may be expected from just under 20 litres, to obtain 2000 horse power it will be found most economical to go to 55 litres. It is suggested that these last two curves shed interesting light upon why it is so difficult to produce a successful large size aero engine, weight considerations necessitating the largest bore and stroke permissible, the latter resulting in a lower rotational speed.

As a complement to the series of composite graphs just illustrated, the five following slides are instructive.

Fig. 3 shows three views and a tabulation of a double row 16-cylinder engine produced by the Bristol Company in 1931. This engine was designed to run at high speed, and with overhead camshafts, but was abandoned chiefly due to the Bristol Company's sleeve valve development. It shows clearly, however, how easy it is to add weight, with an increase of revolutions per minute, and a relatively large number of cylinders, for a given swept volume.





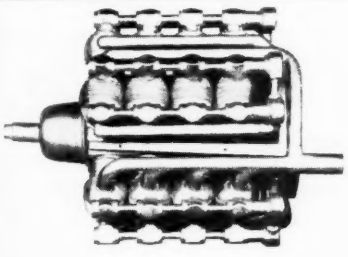


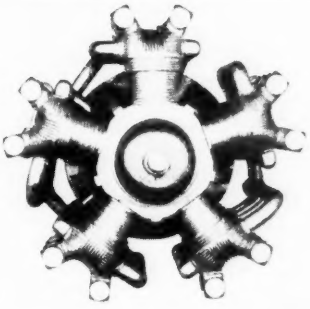
16 CYLINDER AIR COOLED DOUBLE OCTAGON ENGINE

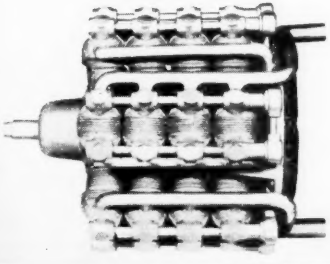
SWEPT VOLUME - 25.7 LITRES (1570 CU INS) NET WEIGHT - 1460 LBS

FUEL OCTANE VALUE	R.P.M.		COMPARATIVE PERFORMANCE							
			'M' TYPE ENGINE				'S' TYPE ENGINE			
			TAKE OFF		ALL OUT LEVEL		TAKE OFF		ALL OUT LEVEL	
	NORMAL	MAXIMUM	B.H.P.	LBS/B.H.P.	B.H.P.	LBS/B.H.P.	B.H.P.	LBS/B.H.P.	B.H.P.	LBS/B.H.P.
73	3000	3450	850	1.72	870 AT 6000	1.68	780	1.87	840 AT 13500	1.74
87	3000	3450	1040	1.4	1020 AT 6000	1.43	900	1.63	1000 AT 15000	1.46

FIG. 3.





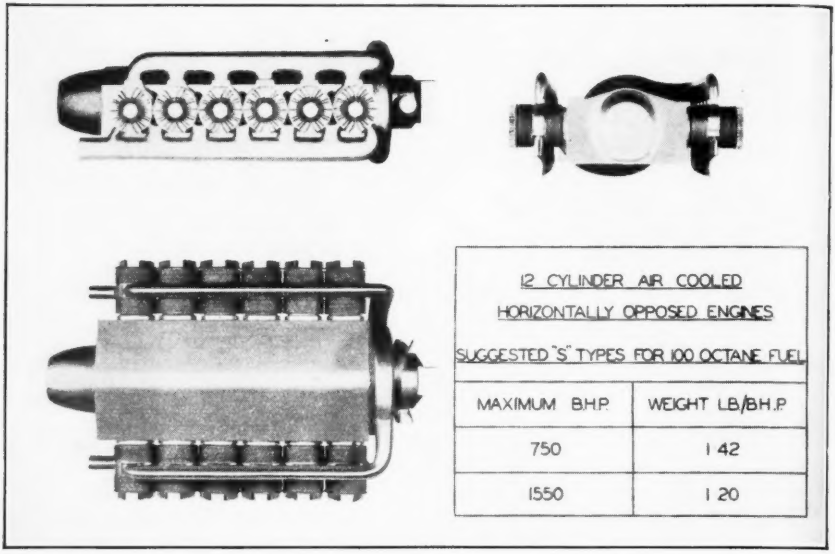


20 CYLINDER 4 BANK RADIAL AIR COOLED ENGINE

SWEPT VOLUME 16.5 LITRES (1005 CU INS) WEIGHT 1450 LBS

DATA FOR PROJECTED 'S' TYPE 100 OCTANE FUEL ENGINE						
R.P.M.		TAKE OFF		ALL OUT LEVEL AT 13000 FT		DIAMETER
NORMAL	MAXIMUM	B.H.P.	LBS/B.H.P.	B.H.P.	LBS/B.H.P.	INS.
3400	3900	900	1.6	1000	1.45	40

FIG. 4.



12 CYLINDER AIR COOLED
HORIZONTALLY OPPOSED ENGINES
SUGGESTED "S" TYPES FOR 100 OCTANE FUEL

MAXIMUM B.H.P.	WEIGHT LB/B.H.P.
750	1·42
1550	1·20

FIG. 5.

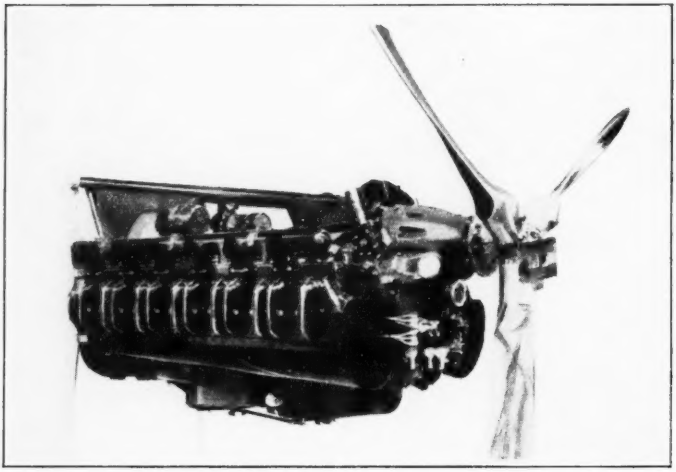


FIG. 6.

THE POTEZ-LORRAINE 12-CYLINDER "FLAT" TYPE ENGINE

Swept Volume (litres).	Rated Altitude (feet).	Maximum B.H.P.	Weight (lbs.).	Weight per B.H.P. (lbs.).
17·7	11500	475	739	1·55

Fig. 4 shows three views of a model of a 20-cylinder multi-bank radial of 1,000 horse power with overhead camshafts, designed, but not actually made, by the Bristol Company, for a similar type of high speed high efficiency engine, and it will be noted that the power weight ratio of this type of engine is also disappointing.

Fig. 5 shows a model of a flat engine to be buried in the wing, with a tabulation of the power and weight, to meet the first and third categories.

Fig. 6 shows the Potez-Lorraine 12-cylinder flat engine which was exhibited at the 1936 Paris Salon. Although this engine does not appear to have been designed for a minimum depth, with a view to burying it completely in the wing, it is possibly an indication of the trend of future design for really high speed aircraft of the smaller category. The weight/brake horse power of this engine is surprisingly low for an in-line layout as will be seen from the tabulation.

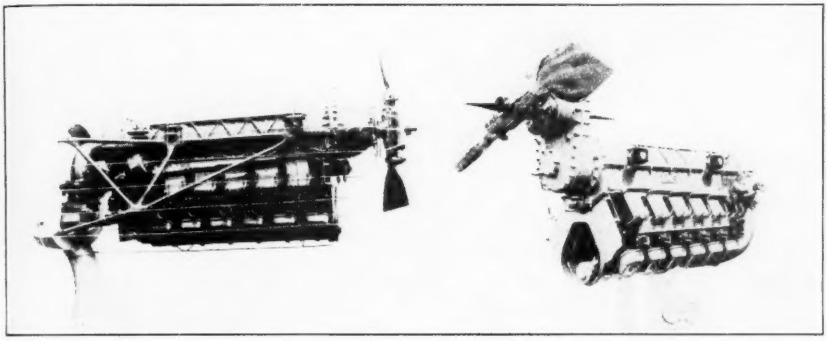


FIG. 7.

THE WALTER "SAGITTA" 12-CYLINDER INVERTED VEE TYPE ENGINE

		Swept Volume (litres).	Maximum B.H.P.	Rated Altitude (feet).	Nett Dry Weight (lbs.).	Weight per B.H.P. (lbs.).	Width (inches).	Height (inches).	Length (inches).
Type	I	18.4	450	6550	815	1.81	28.54	30.75	70.35
Type	II	18.4	470	12100	815	1.73	28.54	38.39	64.17

Fig. 7 shows the Walter Sagitta 12-cylinder inverted Vee engine, which is a good representative type of the moderate power 12-cylinder Vee engine popular on the Continent. Its overall dimensions and weight/brake horse power show the disadvantages of the in-line type in comparison with the radial. The silhouette of the proposed cowling for this engine emphasises the abnormal wetted surface of this type, which matter I shall refer to again later on in the paper.

Output per litre is often considered to be the all important criterion of the engine efficiency. The table shows that this can be somewhat misleading. A tabulation of different types of engines is given on an output per litre basis, and also on a power output per square inch of piston area. It will be seen that this latter is a more valuable guide as to the actual output efficiency of an engine, as it is proportional to the product of mean pressure and piston speed. It will be noted that some engines of high output per litre, owing to their short stroke and low piston speed, are not actually producing as much useful horse power per square inch of piston area as other types with a lower output per litre. Piston speed, as shown in the last column of this slide, is another important problem to explore when reviewing the geometric layout of engines, and, although

ENGINE COMPARISON ON THE BASIS OF B.H.P./SQ. IN. PISTON AREA.

Type.	Capacity (Litres).	Maximum Rating B.H.P.	R.P.M.	B.H.P./ Litre (Corrected to Sea Level).	B.H.P./sq. in. Piston Area (Corrected to Sea Level).	Piston Speed (ft./min.).
Aero Engines.						
Bristol Pegasus XXII ...	28.7	1010	2600	35.2	4.32	3250
Bristol Mercury VIII ...	24.8	840	2750	37.5	3.97	2980
Armstrong Siddeley Tiger IX	32.7	880	2375	26.9	2.64	2375
Napier Dagger III	16.8	805	4000	49.6	3.05	2500
Rolls-Royce " R " (Schneider Trophy)	36.7	2785	3400	75.6	8.20	3450
Pratt and Witney Wasp 1830...	30.0	1100	2650	36.7	3.30	2430
Wright Cyclone " G " ...	29.8	1000	2250	33.6	3.77	2580
Gnome-Rhône 14 N	38.6	1000	2400	28.4	3.02	2000
Gnome-Rhône 14 M	18.9	650	3000	37.7	2.82	2280
Hispano-Suiza 14 AA-OO ...	45.2	1000	2100	22.9	2.52	2340
Renault Coupe Deutsch 12 V...	8.0	450	4500	56.5	3.3	2650
Automobile Engines.						
Austin Racing	0.744	116	7600	155.8	6.54	3240
Talbot 3.5 Litre	3.377	123	4500	36.4	2.63	3310
Ford V 8-85	3.62	85	3800	23.4	1.44	2370

NOTE.—In the case of engines rated at altitude the corrected b.h.p.'s were obtained by adding to the nett b.h.p. the power a blower of 50 per cent. overall efficiency would absorb to raise the mixture from atmospheric pressure to 14.7 lbs./sq. in.

it is not a truly accurate measure of inertia pressures of either pistons or valve gear, it nevertheless is the best criterion of mechanical and breathing difficulties due to velocity.

Balance, firing order, and distribution, are three important factors in the success of a smooth running and satisfactory aero engine, and are governed by the mechanical layout, the first two being determined by fixed mathematical principles, and the third by a combination of timing, and supercharging conditions.

Fuel consumption is an important factor, and is governed by a wide variation of conditions, including the thermodynamic qualities of the cylinder design, valve timing, blower efficiency, distribution, and engine speed. Consumption is also dependent upon the quality of fuel, and, since an up-to-date and efficient aero engine, cruising at 70 per cent. of its power, burns its own weight of fuel in three hours, the importance of this matter should be fully realised.

Accessibility and maintenance, mechanical features affected by the fundamental layout, and sadly neglected in the past, were dealt with fully in my previous paper. I shall have something further to say about accessibility later on in this paper.

When considering the geometric layout of engines, therefore, it is suggested that we must not let our enthusiasm for too small cylinders run away with us. Any move in this direction is always accompanied by a corresponding increase in power/weight ratio and cost of production, and I think we may conclude from this review that, for a given horse power, we should aim at having the fewest number of cylinders as possible commensurate with smooth torque, satisfactory cooling, even distribution, and reasonable mechanical balance.

To cover the four different categories of engine powers suggested as being required for the period under review, it would appear that the most promising layouts will still be divided into two families—radial engines single and double bank, and in-line multi bank.

Fig. 8 is a somewhat ambitious attempt to assess the relative merits of the more conventional layouts of air-cooled engines, from the geometric aspect, for the powers we require, and it is suggested that the increased weight and cost of production of the in-line engines will be sufficiently serious to militate against their introduction for the immediate future, except under special conditions, which will be dealt with later on in the paper.

No attempt has been made to illustrate graphically power, balance, firing order, distribution, and fuel consumption, it being agreed that balance and firing order are satisfactory on all the types considered, and that fuel consumption should be generally similar, but tending to become lower as the number of cylinders have been increased, provided cooling technique is adequate. It should be possible to make distribution reasonably good on all these types, but it seems fair from experience to favour the radial engine on this score in view of the shorter and more symmetrical pipes.

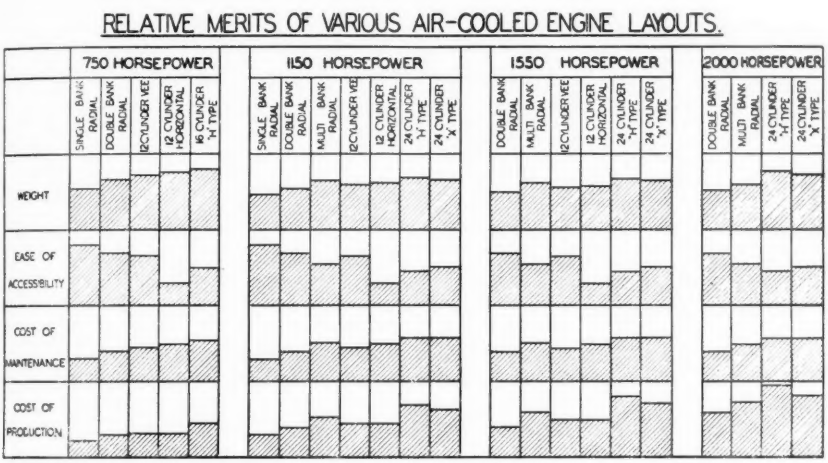


FIG. 8.

(6) ENGINE LAYOUTS FROM THE AERODYNAMIC ASPECT.

The layout of future air-cooled aero engines, from the aerodynamic aspect, embraces a review of the various factors affecting the drag of the complete engine installation.

The main governing factors in aerodynamic layout are shape, overall size or wetted surface, and wing area as a function of the complete nacelle weight including the power plant. These are becoming increasingly important as aircraft speeds rise, and will require the closest co-operation in the future between aircraft and aero engine designers, in fact, for the smallest and highest speed categories of military machines under consideration, I venture to suggest that, within the period under review, a specialised type of engine will have to be produced.

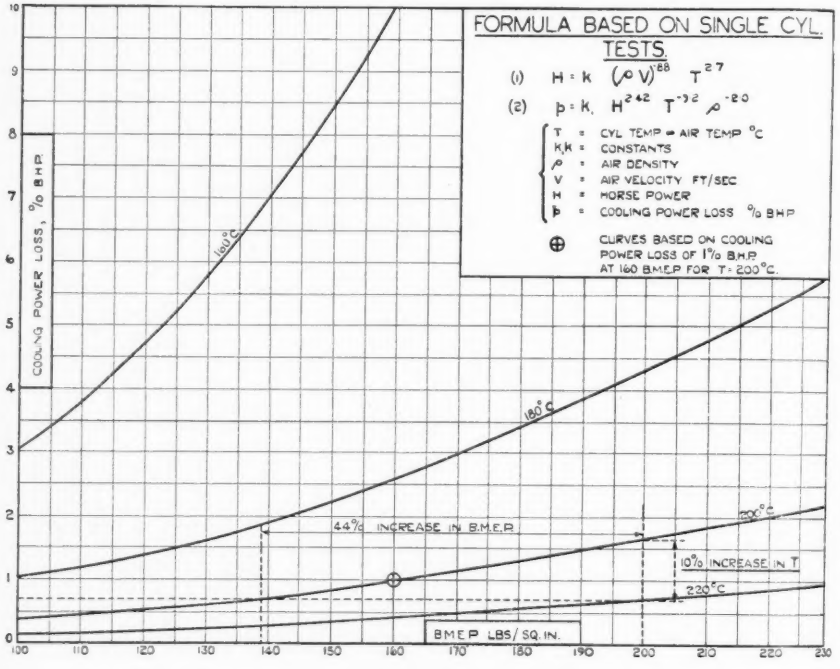
Until quite recently, it was accepted as a fact that any heat dissipating apparatus entailed an increase of head resistance, and the drag due to an engine installation was often assumed to be proportional to the frontal area of the engine plus its cooling system. Fortunately, the advent of ring cowling for the radial engine was the beginning of the end of this fallacy, and recent research work at the Royal Aircraft Establishment has shown that, for overall aerodynamic efficiency, there is little to choose between the best representative types of power plant, the variation of the relative drag contributions, from different sources, balancing out

evenly. At the same time it is believed that there is scope for improvement along certain lines of development in each class.

The drag of a power unit can be broadly divided into three headings:—

(*a*) Drag Due to Cooling Air Flow.

Basically, for any cooling system, a certain weight of air per minute is required. So far as air-cooled engines are concerned, this is a function of cylinder size, fin area, and power output. From this aspect, therefore, there are two distinctive types of layout:—



VARIATION OF COOLING POWER LOSS WITH INCREASING B.M.E.P. (PEGASUS CYLINDER)

Fig. 9.

(1) The in-line, having a relatively large number of small cylinders which favour a reduced mass flow (being the equivalent of an increase in radiator size) at the expense of a higher weight per brake horse power ratio.

(2) The radial, with fewer, but relatively larger cylinders requiring a slight increase in mass flow, but favouring the lowest weight per brake horse power ratio.

To illustrate the magnitude of the mass flow factor on radial engines, tests have been carried out on an unbaffled Bristol "Pegasus" type cylinder, which show that the cooling power loss only varies as the power output raised to the 2.4th power. Since there is no indication that the limit of finning has been reached, this exponent may be reduced by improved technique and development of baffles.

Fig. 9 shows curves, based on this test data, in which the cooling power loss, expressed as a percentage of the brake horse power, has been plotted against the brake mean effective pressure for different working temperatures. The apparatus used did not permit of the actual measurement of cooling power loss, so these curves have been plotted on an arbitrary basis of a 1 per cent. power loss at 160 brake mean effective pressure for a temperature difference of 200° C.

An inspection of this slide clearly shows that over the recommended range of working temperatures, the effect of cooling power loss with increasing brake mean effective pressure is extremely small. The high drag cost of running at too low a temperature is clearly illustrated, and it is interesting to note that a 10 per cent. increase in working temperature permits approximately 44 per cent. increased power output for the same fractional cooling power loss.

Air density is another factor which affects the rate of heat dissipation. In this connection it should be noted that the fall in air temperature with altitude, up to the lower limits of the stratosphere, is more than sufficient to offset this effect, since equation (2) on the slide shows that the cooling power loss only varies inversely as the square of the density, whereas it varies inversely as no less than the 9th power of the temperature difference.

With increased speeds of aircraft, the adiabatic rise in temperature of the cooling air, caused by slowing it down over the surface to be cooled, is becoming a factor of considerable importance, since it varies as the square of the speed, and whilst being only 9° C. at ground level at 300 miles per hour, it becomes 16° C. at 400 miles per hour, and 25° C. at 500 miles per hour. The high temperature of the cooling surfaces of the air-cooled engine, however, will cause it to be less affected by this consideration than other types.

The effect of the compressibility of air on the performance of high speed machines is becoming more serious, and for speeds in excess of 400 to 450 miles per hour, may present a new set of aircraft design problems. This effect, however, is not wholly detrimental, so far as the power plants are concerned, as has been demonstrated by Meredith of the Royal Aircraft Establishment, who has established that a ducted type of cooling system can function as a heat engine—the heat energy imparted to the air, in cooling the engine, being converted to an effective thrust by adiabatic expansion. The thrust obtained, increases approximately as the square of the speed, and Fig. 10 shows the possible gain in thrust horse power with increasing speed for a baffled radial air-cooled engine of 1,000 horse power. The dotted line indicates the theoretical maximum gain, on the assumption that the total velocity head is obtained in the plane of the cylinders by reducing the cooling air velocity to zero, and the full line represents a more practical condition when the " cold " internal cooling power loss is 2 per cent. of the brake horse power. An inspection of this slide shows that, for a total flow of 400 cubic feet/second, the drag, due to cooling at 295 miles per hour, is offset by an effective thrust, and at 410 miles per hour there is a net gain which is equal to 2 per cent. of the brake horse power.

Apart from compressibility effects, there is a further gain to be derived by utilising the kinetic energy of the exhaust gases by reaction in a rearward facing exhaust pipe. Unfortunately, this gain only varies with machine speed, but even so it is more than sufficient to offset the losses due to change of momentum of air used for carburettor and oil cooling—which vary as the square of the speed—and still leaves a balance for effective thrust.

In concluding this section, it can be said that the various authorities dealing with this aspect are agreed that whichever arrangement of power plant is used, the drag caused by cooling air flow is relatively small, being approximately equal to 1 per cent. of the brake horse power, and under certain conditions, natural physical laws function in such a manner as to reduce the drag from this source, and should in fact tend theoretically to produce an effective thrust.

(*b*) Drag Due to Installation of Nacelle on a Wing.

Nacelle form and drag are influenced by the shape of the engine, its overall length, and weight. Broadly speaking, in-line engines are longer than the radial, but have a smaller cross-sectional area.

There are two main problems to be considered under this heading—the reduction of spoiling loss associated with duct entries and reduction of wetted surface. With regard to the former, the present conventional form of cowled radial engine appears to suffer more than the in-line engine in this respect, a contributory factor being a boundary layer breakaway over the airscrew spinner which is in the centre of the duct entry.

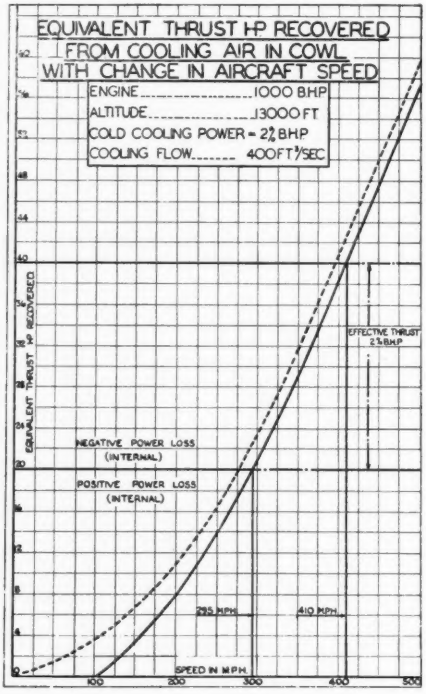


Fig. 10.

Tests carried out in the N.A.C.A. wind tunnels, on radial air-cooled installations, show that, for a given nacelle-wing combination, the maximum propulsive efficiency is obtained with the airscrew located at 30 per cent. of the chord ahead of the leading edge, and tests in this country confirm this for similar geometric arrangements. Research at the Royal Aircraft Establishment also shows that the radial engine nacelle drag is a function of the ratio of wing thickness to engine cowl diameter. As the wing thickness more nearly approximates to the cowl diameter, the drag of the nacelle becomes less, mainly due to reduction of spoiling loss.

From a consideration of pitot entries in the leading edge of the wing, and provided the internal wing structure is arranged for duct cooling and accessibility, the drag, due to spoiling loss and nacelle surfaces, could be practically eliminated by the retraction of the radial engine within the leading edge, on aircraft whose wing thickness equals the engine diameter. Existing test data

indicate that if the airscrew were required to work within 10 per cent. ahead of the chord, its propulsive efficiency would not be appreciably affected. Accordingly, this conception should receive serious attention.

This arrangement will only be possible on aircraft of at least the Short Empire Boat size and proportions, and for the period under review, improvements in detail technique will still be required for a large number of radial engine installations employing conventional nacelles.

To illustrate the relative effect of in-line and radial engine forms on nacelle surface area, I have examined comparative installations on the basis of equal power output, and the principal dimensions are given on Fig. 11. Fig. 1 of Fig. 11 shows an in-line and radial engine mounted on a particular wing on the basis of equivalent balance, the radial engine being mounted normally, and the in-line

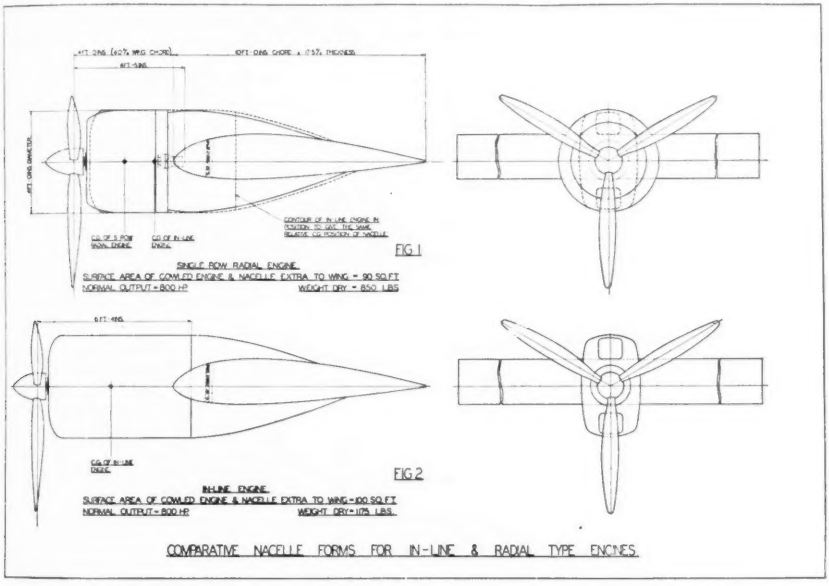


FIG 1
SINGLE ROW RADIAL ENGINE
SURFACE AREA OF COWLED ENGINE & NACELLE EXTRA TO WING = 90 SQ FT
NORMAL OUTPUT = 800 HP
WEIGHT DRY = 850 LBS
FIG 2
IN-LINE ENGINE
SURFACE AREA OF COWLED ENGINE & NACELLE EXTRA TO WING = 60 SQ FT
NORMAL OUTPUT = 800 HP
WEIGHT DRY = 1175 LBS
COMPARATIVE NACELLE FORMS FOR IN-LINE & RADIAL TYPE ENGINES

FIG. 11.

engine being set back, in view of its greater weight, to keep the centre of gravity of the aircraft in the same position. Fig. 2 of Fig. 11 shows the in-line engine mounted to clear the wing structure. The difference in wetted area additional to wing in Figs. 1 and 2 is small, but does in fact favour the radial type.

Fuselage interference effects, and in many cases the housing of a mechanically retracting undercarriage, need careful consideration in deciding upon the design of the nacelle, and its position in relation to the wing, if the minimum drag is to be achieved, and a compromise generally has to be made after consideration of all the factors involved. Such research as has been carried out on full-scale installations to date, indicates a form drag with nacelles irrespective of the type of engine enclosed, and by the reduction of this drag in common with the development of the technique of surface finish on the complete aircraft, there is an appreciable gain to be derived.

It is in this connection that full-scale research can be so useful. There is a fund of information, based on model tests, relating to the drag cost of mounting a nacelle on a wing, from which certain inferences can be drawn, but there is a

very urgent need for further full-scale *ad hoc* research on practical installations, for each type of power plant, to confirm how closely, in actual practice, the technique of design and finish of the manufactured components agree with small tunnel results.

Until such a connected series of tests is carried out it will be impossible to assess, with complete accuracy, the relative drag costs of representative power units mounted on a wing.

There is some evidence to show that, on a radial air-cooled engine, an improvement is to be obtained by deleting the conventional controllable gill exit, and ducting the cooling air to the trailing edge of the wing. Fig. 12 has been prepared to show the application of this principle on a double-row installation. The nacelle has been dropped and provision made for the retractable undercarriage. The lines of the duct are indicated in the plan and elevation of the nacelle; the sections show the passages on either side of the wheel housing. A controllable flap at the exit will be required to induce flow through the duct for engine running on the ground and in climbing flight. The passage areas are arranged so that the air velocity does not exceed 100 miles per hour.

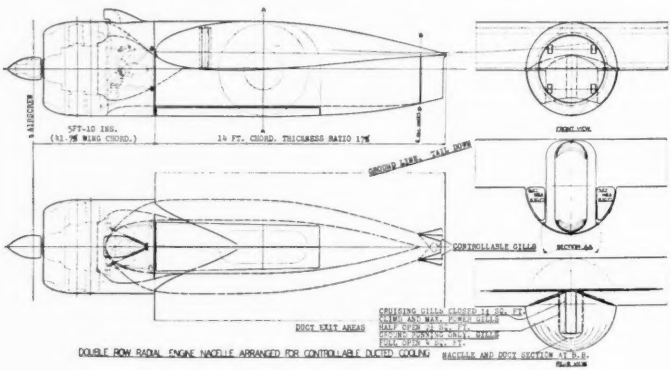

5FT-10 INS.
(43·7% WING CHORD.)
14 FT. CHORD. THICKNESS RATIO 17%
GROUND LINE. TAIL DOWN
CONTROLLABLE GILLS
SECTION AA
DUCT EXIT AREAS
DOUBLE ROW RADIAL ENGINE NACELLE ARRANGED FOR CONTROLLABLE DUCTED COOLING
NACELLE AND DUCT SECTION AT B-B.

FIG. 12.

Summarising this section, it may be said that there is scope for improvement in installation technique for both the radial and in-line types of power plant. In comparing nacelle forms on a surface area basis, there is little to choose between them, but the in-line type has the advantage so far as duct entry and spoiling losses are concerned. On such installations as would permit of the engine being housed in the leading edge of the wing, however, the lighter radial engine will have the advantage.

(*c*) Drag Equivalent of Power Plant Weight.

In section (5) of this paper I have endeavoured to outline the main characteristics affecting engine weight and its effect upon simplicity, maintenance, and prime cost of the power plant. Weight, however, must also be reviewed from the aerodynamic aspect as producing an additional drag equivalent of the complete power plant.

It has been pointed out under item (*b*) of this section that the relationship between the wing thickness and cowl diameter influences the nacelle drag, and, with increased wing thickness, the rate of gain will favour the radial, since the improvement is largely associated with the reduction of duct entry loss.

Probably with this point in mind, small diameter double row radial air-cooled engines have recently been developed for high speed twin-engined military

aircraft, and were prominent features of the last Paris Salon. I have given some considerable thought to this development, and have explored the merits of the two-row radial as compared with the single bank, in this category, with regard to mechanical layout, weight, and cost.

Some few years ago, when the results of the Schneider Trophy machines were fresh in our minds, there was a slogan—that reduction in drag equivalent to 1lb. at 100 feet per second would be equivalent to a permissible increase in weight of 100lbs. This statement is open to misinterpretation, and to arrive at a proper relationship, the weight factor must be considered as affecting wing surface drag, landing speed, etc., of the aircraft.

How important this weight factor is can best be illustrated, I think, by a definite example. Captain Barnwell has examined the comparative performance of two twin-engined single-seater fighters, having double-bank and single-bank radial engines respectively, and for the purpose of comparison, the wing loading on the two aircraft is constant, so that the landing speeds are the same. The relevant figures of engines and aircraft are shown in the following table, from which it will be seen that the top speeds of the two aircraft are approximately equal, the drag of the increased wing surface, due to the extra weight of the small double-row engine, offsetting the increased nacelle drag of the larger but lighter single-row type.

EFFECT OF POWER PLANT WEIGHT AND DIAMETER.
COMPARATIVE PERFOMANCES OF TWIN-ENGINED FIGHTERS.

Case I.—Single row 9-cylinder engine.
Case II.—Double row 14-cylinder engine.

Item.	Case I.	Case II.
Engine diameter	46.5in.	40.0in.
Engine power	750 h.p.	750 h.p.
Engine weights (nett dry)	1,640lbs.	2,000lbs.
Power plant accessories:—		
Airscrews, exhaust systems, controllable cowls, engine mountings nacelle structure, starting gear, oil coolers, fuel and oil systems, engine controls and instruments, intakes, filters and pumps with drives	1,450lbs.	1,450lbs.
Fuel, oil and tanks ($1\frac{1}{4}$ hrs.) ...	865lbs.	865lbs.
Military load	1,150lbs.	1,150lbs.
Structure weight	2,183lbs.	2,425lbs.
Total weight	7,315lbs.	7,890lbs.
Wing area	244 sq. ft.	263 sq. ft.
Wing loading	30 lbs./sq. ft.	30 lbs./sq. ft.
Power loading	9.75 lbs./h.p.	10.5 lbs./h.p.
Top speed	375 m.p.h.	376 m.p.h.

Fig. 13 shows a view of a scale model of these two engines mounted on the leading edge of a suitable wing.

By analogy, I think it would be fair to state that, on comparable aircraft designed around the radial and in-line engines, little advantage can be claimed by either in regard to the relative wetted surface and overall drag.

After examining further the various factors that affect engine layout, from the aerodynamic standpoint, and assessing the various drag figures, as shown in the following table, there does not appear to be any appreciable advantage with

any one type, so that the final verdict will have to be obtained from the consideration of other qualities, such as first cost, production in time of emergency, installation simplicity, easy maintenance and repair, and fuel consumption.

INSTALLATION DRAG OF RADIAL *v.* IN-LINE AIR-COOLED ENGINES.

	Radial.	In-line.
Maximum power (100 octane)	800 h.p.	800 h.p.
Weight—nett dry	850lb.	1,175lb.
	Drag at 100ft. per sec.	
Total internal cooling drag	1.5lb.	0.5lb.
Nacelle drag	7lb.	7lb.
Drag, due to difference in power plant weight (wing loading 25 lb./sq. ft.)	—	1lb.
Total	8.5lb.	8.5lb.

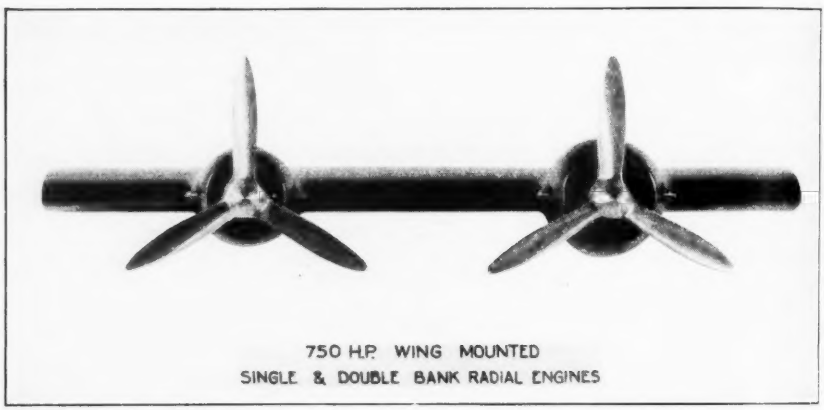


FIG. 13.

I think that low power weight ratio will always be of fundamental importance, and it would appear that the only justification for departing from this characteristic would be the introduction of specialised engines completely buried inside the wing.

(7) STANDARDISATION OF COMPLETE POWER UNITS.

The standardisation of all aircraft components is one of the most pressing needs of the industry to-day. Progress of aircraft design has not always assisted in this respect, since it has usually been achieved in the past by change and fundamental difference of construction. Until comparatively recently the bulk of machines were of biplane form, and the location of power plants varied with each individual design, so that any question of a standard power unit was a practical impossibility. Fortunately, to-day, progress has been achieved along lines which facilitate the adoption of this principle, due to the localisation of power units on monoplane wings.

The standardisation and supply by engine constructors to aircraft manufacturers of complete power units, ready to instal in the aircraft as opposed to the supply of bare engines, is a broad subject almost worthy of a paper on its own. Nevertheless, in this section a brief reference will be made to this important

subject, because so much interest is being taken in it at the present time, and because it is a matter which it is envisaged must be tackled, and put upon a proper basis during the five years under review.

From the economic standpoint, the saving in cost and time of the design staffs, together with the simplification of stores equipment, would be of considerable value to the Royal Air Force, aircraft constructors, and civil operating companies. An equally, or even more, important economy to be effected by the use of the standardised power unit, as compared with the conventional installation, is the saving in time during which an aircraft would be out of commission when it is necessary to change engines.

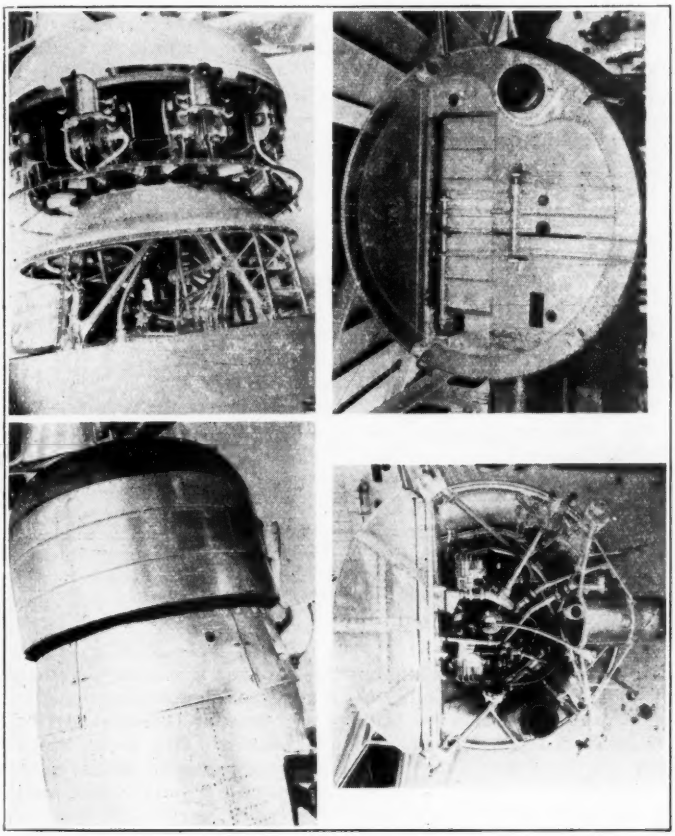


FIG. 14.

Air-cooled power plants generally, and particularly air-cooled radial engines, are especially suited to this standardised unit construction, and it is suggested that it will be worth while reviewing this matter in order to see upon what lines standardisation can be most readily achieved.

Some 14 years ago the Bristol Company endeavoured to introduce such a system, and pioneered an engine unit on the swinging mounting principle, hinged at the bulkhead. This was successfully tested out on a number of machines,

and although it achieved a measure of success, the scheme was before its time and did not receive serious support. Recently this matter has again come into prominence, and modern examples of single and multi-engined installations show that the present trend in design readily lends itself to the principle of standardised power units for radial air-cooled engines.

In these installations, the exhaust system, removable cowling, and controllable gills, are standardised units, built into the aircraft by the aircraft constructor in collaboration with the engine maker. This is only the commencement of what can be accomplished, now that modern aircraft are stabilised into a more concrete series, and it is suggested that the scope should be considerably extended, the engine constructor providing a quickly removable engine mounting plate, together with a standardised frame structure between it and the fireproof bulkhead; within this space a number of engine components would be installed in a manner best suited for their proper functioning, accessibility, and to facilitate easy power unit removal.

Considerable progress has been made along these lines in the U.S.A., and Fig. 14 show views of the " Pegasus "—" Douglas " installation, with standardised power unit construction.

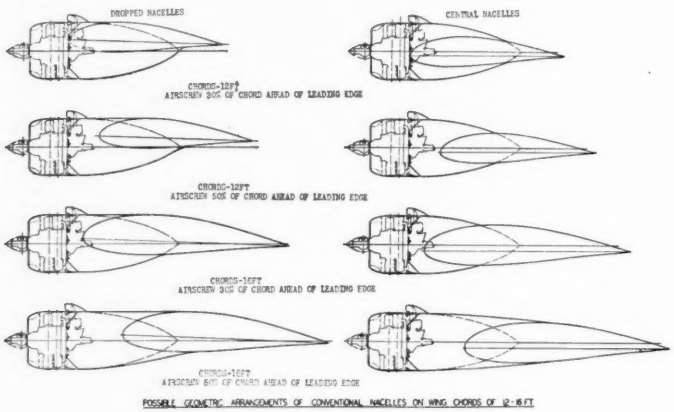

DROPPED NACELLES
CENTRAL NACELLES
CHORDS-12FT
AIRSCREW 30% OF CHORD AHEAD OF LEADING EDGE
CHORDS-12FT
AIRSCREW 50% OF CHORD AHEAD OF LEADING EDGE
CHORDS-16FT
AIRSCREW 30% OF CHORD AHEAD OF LEADING EDGE
CHORDS-16FT
AIRSCREW 50% OF CHORD AHEAD OF LEADING EDGE
POSSIBLE GEOMETRIC ARRANGEMENTS OF CONVENTIONAL NACELLES ON WING CHORDS OF 12-16 FT

FIG. 15.

Top left is an exterior view of the nacelle—top right is a view of the nacelle with cowling removed, showing the grouping of pipe connections at the bulkhead—bottom left is a rear view of the power unit on a sling ready for assembly, complete with cowling, exhaust, and oil systems. Two hours are allowed for installation in air frame ready for running—bottom right is a view of the fireproof bulkhead, showing four engine mounting attachment points of the " Lord " flexible type, electrical plug connections, engine controls, etc.

All multi-engined aircraft will have their power eggs in nacelles mounted centrally or dropped, relative to the wing, according to design requirements.

It is appreciated that wing chords will vary with different designs, and Fig. 15 shows a series of geometric arrangements that are possible on a radial installation with wing chords of 12 and 16 feet. The diagrams on the left illustrate dropped nacelles, and on the right central nacelles, in each case with the airscrews located at 30 and 50 per cent. of the chord ahead of the leading edge.

Installations employing conventional controllable gills should be arranged so that the gill exit has a reasonable clearance ahead of the leading edge. The

engine could be located nearer to the wing when ducted installations are used, and although a standard mounting structure is not incompatible between the two systems, the latter might restrict the disposition of attachment points on the normal fireproof bulkhead line.

The principal dimensions and anchorage points must be common to all of these alternative arrangements, viz. :—

(1) The distance between the normal bulkhead and the engine.
(2) The four attachment points on the plane of the bulkhead.

The following design considerations will decide the position of these four points :—

(*a*) Type of construction and form of the after body nacelle—monocoque or strut braced.
(*b*) Undercarriage and wheel housing.
(*c*) Oil tank and oil cooler installation.
(*d*) Provision of sufficient space for cooling air flow in the case of the completely ducted installation.

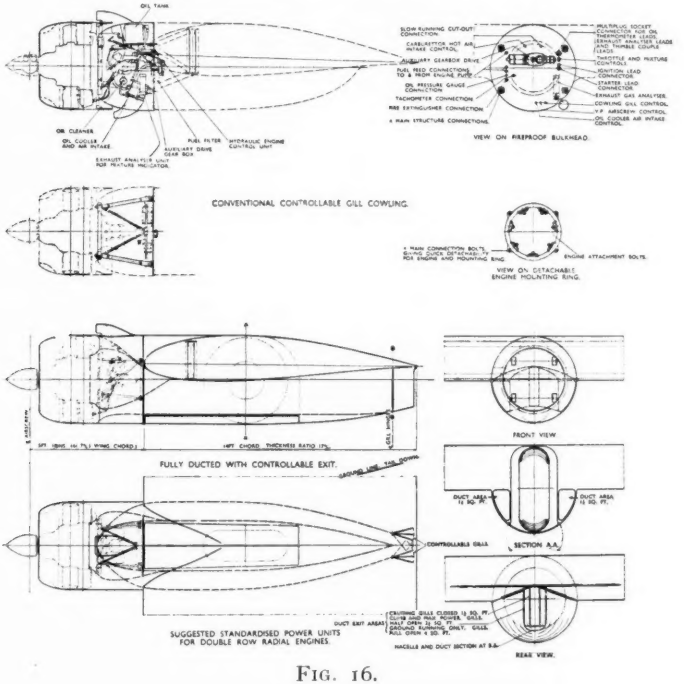


FIG. 16.

Fig. 16 shows diagrammatically two alternative cooling systems arranged for completely standardised power units, one by the conventional controllable gill, and the other by adjustable exit at the trailing edge, on the underside of the wing.

It is suggested that the engine mounting might consist of a triangulated tubular structure attached to four standardised, and accurately jigged, structural points on the bulkhead. These joints can be conveniently arranged for a ball-ended spherical housing.

The front end of this structure would be finished by four bolt-ended sockets, to which a quickly detachable engine plate could be mounted. The engine would

be attached to this plate in the normal manner, either rigidly or through suitable rubber mountings.

This apparent duplication would serve a dual purpose, in that the complete mounting, with accessories, could be standardised for production, but, in certain cases, operators would have the option of detaching the engine complete with mounting plate if they did not wish to carry duplicate structures, oil tanks, etc.

The complete unit should include provision for the following services and accessories, which can be divided into six groups:—

Group I. An auxiliary which may be driven through the single drive remote gearbox.

(1) Electric generator.
(2) High pressure air compressor.
(3) Low pressure air compressor.
(4) High pressure fluid pump.
(5) Vacuum pump.

Group II. Units which may be located on, and detached with, the engine mounting.

(6) Oil tank.
(7) Oil cooler.
(8) Oil cleaner.
(9) Starter magneto.
(10) Exhaust gas analyser.
(11) Fire extinguishing system.

With this arrangement of engine and auxiliary units the number and type of connections which must be broken to permit removal of the power unit can also be divided into groups.

Group III. Electrical connections.

(12) Engine starter leads.
(13) Ignition leads.
(14) Thimble couple leads.
(15) Oil thermometer leads.
(16) Exhaust gas analyser leads.

Group IV. Hydraulic or union connections.

(17) Petrol feeds (to and from engine driven pump).
(18) Oil pressure gauge.
(19) Boost gauge.
(20) Fire extinguishing system.

Group V. Mechanical connections.

(21) Carburettor hot air intake control.
(22) Carburettor slow running cut-out control.
(23) Oil cooler air intake control.
(24) Controllable pitch airscrew control.

Group VI. Other connections with alternative methods of operation.

(25) Throttle and mixture controls—mechanical or hydraulic.
(26) Tachometer—mechanical coupling or electrical.
(27) Variable cowling gill control—mechanical or electrical.

The scope of this subject is too great to be fully reviewed in the short space of time at my disposal, but the uniformity of the design of modern aircraft has brought us to a stage where the principles enumerated above must be seriously considered for each type of engine, and brought to a satisfactory conclusion.

It is appreciated that it is not likely that it will be possible to have only one standardised power unit for each type of engine, but it is hoped that it may be possible to limit the number to two.

(8) Conclusions.

Having briefly touched on what is believed to be the main factors governing the trend of air-cooled aero engines for the next five years, and having suggested the four types of engine which I think will meet military and the larger civil transport requirements during this period, I will conclude by endeavouring to sum up the most promising layouts for these four sizes, in the hope that this may promote discussion and prove helpful to the air-cooled aero engine designer in deciding which road he must pursue for the immediate future.

Earlier in this paper it has been suggested that the trend will be towards multi-engined aircraft for all purposes, and these conclusions are based on this definite opinion.

Undoubtedly, as aircraft design and manufacturing technique advances, so the total drag of aircraft will approach more closely to the ideal as expounded by Professor Melvill Jones, namely, that due to turbulent skin friction. Will aeroplane designers eventually be satisfied to meet these conditions with conventional power plant as they know it to-day? It would appear to me that, to cope with this problem, the general trend will be to submerge power units entirely within the envelope of the wing if these ideal results are to be obtained. Can such fundamental changes in the layout of the four suggested sizes of power plant be envisaged in five years, and are they necessary in all four categories? Can the difficulties outlined in this paper be overcome, as well as the many problems affecting the aircraft which would be necessary with such a drastic change of power plant layout?

I would suggest that a complete change over of all four categories of engines is out of the question in the period under review, and will most probably never be required, since, in the larger classes where four or more engines will be standardised on one aircraft, the wing thickness will be such as to permit of the radial engines being housed inside the leading edge. Quite apart from the engine designers' problems, there are so many basic aircraft ones to settle also, which become increasingly difficult the greater the number of engines employed.

Full-scale research work must be undertaken in regard to the position of airscrews on the leading edge of the wing, the effect on the wing and spar designs of accommodating the engines accessibly, and dealing with the stowage of undercarriages, and a host of other fundamental problems.

I suggest that drastic changes of this sort must come into being, and be investigated on one type first, as we have seen in the case of the classic Douglas series, and the placing of the engine inside the envelope will, in my opinion, first come into being in the smallest category.

My interpretation of the four sizes of engines, during the period under review, would therefore be as follows:—

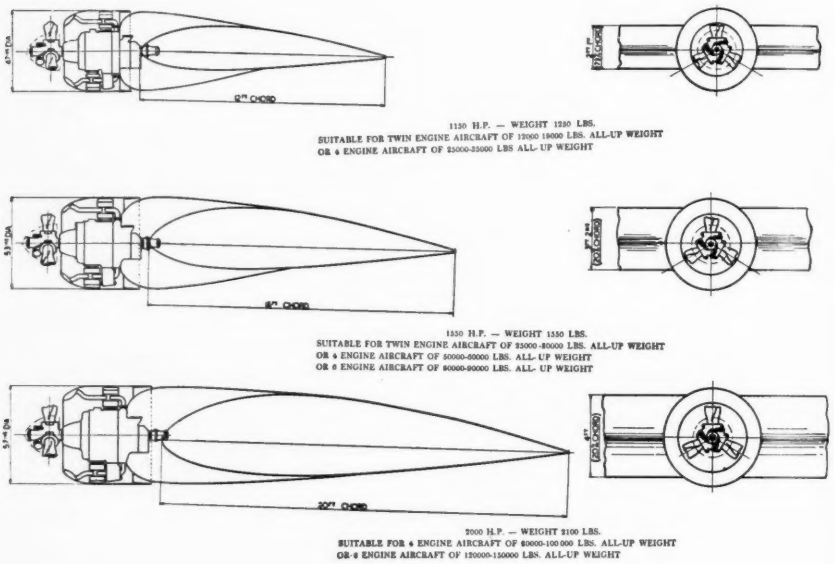
(1) The first category—750 horse power for 820 lbs. weight is suitable for twin-engined civil and military aircraft. I would suggest that this size of engine is suitable for twin-engined destroyer or multi-place fighter types, and in the period under review, I think there is justification for serious consideration of the flat engine entirely buried in the envelope of the wing for these types of aircraft. Some 18 months ago, the Bristol Company produced a layout for such an engine, but urgency of other work, and the need for an entirely new technique of aircraft design, prevented it receiving very serious consideration. Provided a sufficiently bold and specialised step can be justified, for military purposes for the highest speeds, it is believed that this is the ideal solution for the future, for the smallest category of engine, and apart from the fact that the engine drag approaches the ideal solution, an aircraft so equipped has many other advantages.

It is suggested that the radial engine is the ideal form in this category for more general purpose and civil types.

From designs by Captain Barnwell of aircraft with the flat engine compared with the radial, it would appear that two types of engine will have to be envisaged for this category—the radial engine in compact form, and the specialised flat

engine. Sacrifices in regard to weight, cost, simplicity, etc., will all have to be made on account of the flat engine, and many problems in regard to installation carefully investigated.

(2) For the other three categories of engines, viz.: 1,150 horse power for 1,250 lbs., 1,550 horse power for 1,550 lbs., and 2,000 horse power for 2,100 lbs., it is firmly believed that the radial engine will hold its own during the period under review. For the sizes and speeds of aircraft envisaged for which these engines are intended, it is submitted that the Royal Aircraft Establishment, and other authorities, have demonstrated that it will be possible to achieve even lower drag installations than at present in vogue, by retracting the radial type of engine towards the leading edge of the wing, in conjunction with duct cooling. Fig. 17 shows in sectional form, conventional double-row radial engines to meet the last three categories of power plant.


42" DIA
92" CHORD
1150 H.P. — WEIGHT 1250 LBS.
SUITABLE FOR TWIN ENGINE AIRCRAFT OF 12000 18000 LBS. ALL-UP WEIGHT
OR 4 ENGINE AIRCRAFT OF 25000-35000 LBS ALL-UP WEIGHT
53" DIA
82" CHORD
1550 H.P. — WEIGHT 1550 LBS.
SUITABLE FOR TWIN ENGINE AIRCRAFT OF 25000-40000 LBS. ALL-UP WEIGHT
OR 4 ENGINE AIRCRAFT OF 50000-60000 LBS. ALL-UP WEIGHT
OR 6 ENGINE AIRCRAFT OF 80000-90000 LBS. ALL-UP WEIGHT
54" DIA
202" CHORD
2000 H.P. — WEIGHT 2100 LBS.
SUITABLE FOR 4 ENGINE AIRCRAFT OF 40000-100 000 LBS. ALL-UP WEIGHT
OR 6 ENGINE AIRCRAFT OF 120000-150000 LBS. ALL-UP WEIGHT

COMPARISION OF WING MOUNTED DOUBLE BANK RADIAL ENGINES

FIG. 17.

I am somewhat diffident about expressing any opinion on the section of the wings under consideration, and expect criticism on this score, but they have been put forward only as a basis of discussion. It is appreciated that wing design is dependent upon a number of factors, such as type of construction, speed, operational altitude, etc., and in this connection, it will be useful if some advice can be given as to the trend of wing thickness for the future, as it seems that this may have a considerable bearing on engine layout.

To sum up, during the next five years, it would appear that the smaller the size of the aircraft the more difficult it is to obtain a suitably scaled radial or in-line engine of sufficient power, whereas the larger the size of the aircraft the less it seems can be said against the radial, in fact, in the largest category, the engine is almost entirely lost in the section of wing.

The wetted surface of a ducted radial engine of this size must be a very small proportion of the total wetted surface of the aircraft. Such engines would be required for a large civil flying boat or long range bomber, cruising at 250 to 275 miles per hour, and it is assumed that the thickness of wing shown in the diagram would be quite permissible.

So much for my summing up of the possible layouts for the four sizes of air-cooled aero engines required for the next five years of aircraft development. I have endeavoured to be unbiased in this analysis, and have made it with the hope of obtaining constructive and helpful criticism from the aircraft designer, as it is believed that every engine designer is anxious to learn all he can before finalising his new series of engines for 100 octane fuel.

I should like to proffer my thanks to the Bristol Company, and others, for permission to show slides, and to members of my staff for helping me, especially Messrs. Mansell and Copley, in the preparation of diagrams and tabulations.

Discussion.

Mr. F. R. Banks (*Fellow*): He wished, on behalf of those present, to congratulate Mr. Fedden on his excellent paper, and he thought it was one of real value because it gave a forecast of engine types and designs which was valuable, and almost essential, if they were to progress in aviation. Although he had been asked to discuss the fuel situation Mr. Banks said that this was a matter rather for the fuel companies, because he personally knew little or nothing about the prices of fuels upon which so much depended when making comparisons between compression ignition engines and petrol engines. He sympathised with Mr. Fedden in the difficulty that he, Mr. Fedden, had in getting an accurate estimate of the price differential between 100 octane fuel and fuel oil for C.I. engines. This price differential was practically the key to the whole situation, and upon it depended the question as to whether it was worth while developing the C.I. engine or not. One could only guess at the future prices of fuels, and he did not think the fuel companies themselves were in a position to forecast prices five years hence. He seemed to remember that a few years ago Mr. Fedden, in answer to the question as to whether it would be worth while developing the C.I. engine, had said that it would require about £250,000 to make one which would satisfactorily compete with the, then, present-day petrol engine.

He suggested that Mr. Fedden had been a little conservative in quoting the consumption of the 100 octane petrol engine as 0.435lb. per b.h.p. hour; if the same degree of development were devoted to the petrol engine in the future as would have to be devoted to the compression ignition engine in order to ensure the success of the latter, it could safely be said that a consumption as low as 0.38lb. per b.h.p. hour, or even lower, was possible with the petrol engine. He thought that the fuel consumption quoted for the C.I. engine by Mr. Fedden (0.38lb. b.h.p. hour) was fairly safe, and on the basis of the Junkers developments it should be possible to reduce this to about 0.36lb. per b.h.p. hour. Even then the 100 octane petrol engine would show to advantage.

There was one aspect of the C.I. engine which might prove an advantage for high altitude flying. Due to the fact that large capacity blowers would be necessary in order to restore sea level power at high altitudes, this would involve high temperature boost which, in the case of the petrol engine, would necessitate the use of intercoolers, probably of fairly large proportions, but in the case of the C.I. engine it would not matter if the boost temperature were on the high side and intercoolers should not be necessary. Therefore, whatever the C.I. engine lacked in power output as compared with the petrol engine might be counter-balanced by reduced drag in not having to tow an intercooler through the air. Also, since the heat rejection to the exhaust was lower in the case of the C.I. engine a turbo supercharger could be more easily developed for this type of engine, and in the speaker's opinion should be regarded as an integral part of the C.I. engine and developed with it.

The beauty of the C.I. engine was that test bed fuel consumptions could always be reproduced in the air, and this was not yet the case with the petrol engine, and considerable complication and instrumentation was necessary in order to control this factor with the latter engine. However, assuming equal development of both types, it should certainly be possible to reproduce the low fuel consumptions, already obtained on the test bed with the 100 octane petrol engine, in the air. Since the " constant volume " cycle of the petrol engine was more efficient thermally than that of the C.I. engine for a given compression ratio, it was possible with further development to bring the fuel consumption of the former well below that of the latter, but this might involve excessive maximum combustion pressures which would prove very difficult to deal with.

In a quest for further information and without any desire to be critical, he would like to comment upon the statement in the paper to the effect that up to the lower limits of the stratosphere the fall in air temperature with altitude was more than sufficient to offset the effect on cooling due to lower density. In that connection he referred to a paper by C. F. Taylor entitled " The Next Five Years in Spark Ignition Aviation Engines," published in the Journal of the Aeronautical Sciences, January, 1937. In that paper it was stated that:—

> " The fundamental disadvantage of the air-cooled engine has to do with flying at high altitudes supercharged to nearly sea-level power. If constant engine power is assumed, the airplane speed will be roughly proportional to the inverse square root of the density. Heat transfer per unit area will be roughly proportional to the product of the density times, the velocity raised to the eight-tenths power and the temperature difference between the air and the radiating surface. Combining these two considerations, a ' cooling factor,' proportional to the four-tenths power of the density times the average temperature difference, can be derived."

A figure (Fig. 3) in Mr. Taylor's paper showed the " cooling factor " in question as a function of altitude for three assumed radiating surface temperatures. The speaker felt that Mr. Fedden's assumption would hold good up to about 20,000ft. and provided that the temperature of the cooling surfaces was comparatively low; but in the case of an engine operating at a reasonable proportion of its maximum power at altitude, and where the normal cooling surface temperatures might be expected to be on the high side, he thought that density would have considerable influence on the cooling of the engine. In this connection it might not be safe to base one's calculations on the average temperature of the engine cooling surfaces, but rather to take the point of highest temperature on the cylinder head because this point would be the most critical. So far, they had little or no experience of these conditions, that is to say, high altitude flying involving a high proportion of the maximum output of the engine. It would be interesting to know what American experience is in this connection because certain experiments have been carried out there with air-cooled engines fitted with turbo blowers, and data should be available which, when published, would give them a definite answer to this somewhat vexed question.

When he had presented his recent paper on " High Duty Aero Engines and Their Fuels," he had been asked whether lower octane number fuels could be used at the higher altitudes by reason of the " better cooling and probably lower B.M.E.P. " of the engine. However, for the reasons stated, he did not think engines would be operated at a very low specific power rating, and if Mr. Taylor were right they would require as high an octane number fuel as they could get. This is particularly the case since high boost temperatures may be expected with engines rated at these altitudes (20-30,000ft.) and also " lean " mixture operation will be required. In addition there will probably be the usual competition between the air transport companies, and high cruising speeds will have to be maintained. The speaker did not know what was meant nowadays by the term " high altitude machines "; it might mean machines for use at 20,000ft. or 30,000ft., and the

operating altitude, whether the former or the latter, would make all the difference in the world to the cooling requirements of an engine.

Mr. Fedden made a statement that on general principles the greater the number of cylinders per unit volume the greater was the weight, and the smaller the volume of the engine the higher the specific output that might be expected. The speaker thought that Mr. Fedden was correct when considering present-day engines, but thought that all the small bore high speed engines, which had been developed to date, had not been pushed enough so far as piston speed and boost were concerned. It was not denied that the small cylinder could stand more punishment than the large one, and he felt that the designers of the so-called high speed types had not yet taken full advantage of the possibilities inherent in their engines

With regard to engine weight; did this matter so much as was indicated? Assuming the same specific fuel consumption for two engines, and also the same maximum power output for each, if the one having the smaller bulk was say 100lbs. heavier than the other (assuming about 1,000-1,200 b.h.p. maximum), would not this extra weight be offset by reduced drag, etc.? Again, concerning the relative effect of in-line and radial engine forms on nacelle surface area, it would be interesting, in view of Mr. Fedden's comments, to know whether any full-scale experimental investigation had been done with regard to the question of the effect of wetted surface on drag. It might have a large effect at high speeds around 300 m.p.h. or it might not, but there was considerable doubt about the whole matter. Whilst he was not in a position to quote any figures, he thought a good comparison might be made between the racing Caudron machine, which was taken over to the States last year, and the high performance American racing machines, fitted with radial engines, which it beat in competitive events. This machine had an in-line engine which appeared to present considerable wetted area relative to that of the fuselage and compared with a radial engine installation.

Major F. M. Green (*Fellow*): One of the most remarkable advances resulting from recent work was in connection with the drag of air-cooled engines. He had been connected with the development of air-cooled engines for a long time and had never looked forward to the day when they could say that the cooling drag of an air-cooled engine would be no higher than that of a liquid-cooled engine, and that in any case it might be negative, so that it would not matter very much. The results achieved represented a tremendous step forward, and it was due very largely to the excellent work on installations at Farnborough and elsewhere. Commenting on Mr. Fedden's call for more full-scale flying in order to determine with greater accuracy the drag of the engine nacelle on the wing, Major Green suggested that the work could best be done in the big wind tunnel at Farnborough. Some very good work had been done there already, and it seemed that it would always be much less costly and easier to do a job like that in the big wind tunnel (assuming that one could arrange the conditions reasonably right) than to do it by flying a full-size aeroplane, in which latter case it was necessary to work by differences, and the accuracy was very much less. If the air speed were not sufficiently great, the best thing to do was to carry out further work with a view to improvement in that respect.

The remarkable improvements effected in the petrol engine by Mr. Fedden and his staff seemed to indicate that some of the best brains were at Filton. Did he advocate that these workers should transfer their attention to the development of compression ignition engines and should leave the excellent work they were doing for the petrol engines? Otherwise, Major Green wondered where Mr. Fedden would find the best brains.

Major R. H. Mayo (*Fellow*): He recalled the very interesting paper from Mr. Gouge a short time ago on the development of flying boats, when he had expressed great appreciation on behalf of Imperial Airways of the splendid contribution to the development of the flying boat which Mr. Gouge had made during the last 10 or 12 years. He would now like to say that without the contribution

made by Mr. Fedden and the Bristol Company the standard of performance of the " Empire " series of flying boats would have been far below that which had in fact been achieved. One of these boats, the " Caledonia," had that day (February 18th) flown non-stop from Calshot to Alexandria, a distance of more than 2,200 miles, at an average speed of more than 160 m.p.h. That sort of performance with a comparatively new aircraft and installation indicated that there was not much wrong with the engines.

It was a matter for the greatest satisfaction that Mr. Fedden had come into the open and had expressed strong support of the compression ignition engine. Imperial Airways had for a long time past realised the great advantages of the compression ignition engine for long-range work; but unfortunately they had not been able to achieve their desires in that direction because there had been no compression ignition engine available and no prospect of getting one. The trouble was that the market for the compression ignition engine in commercial aviation was so small that there was no possibility of commercial aviation finding the money for the development of that type of engine. It seemed that that was a function which the Government ought to perform. Whilst he appreciated that the Government's hands were very full at the present time and would be full for some time to come, he believed strongly, with Mr. Fedden, that the compression ignition engine ought to be developed, for he felt sure that money invested now in the development of that type of engine would prove within the next five years to have been very well spent.

Although Mr. Fedden had mentioned many of the important advantages of the compression ignition engine, there were one or two others which he had not mentioned. It seemed that the elimination of the ignition system, from the point of view of maintenance and reliability, would represent a great step forward, because he was afraid it must be admitted that the development of what might be called the " accessories " of the engine had not kept pace with the development of the engine itself. Another matter which would be of great importance, certainly in commercial aviation, and also most likely in military aviation, was the advantage which the compression ignition engine had in regard to simplicity of control, from the pilot's point of view. He believed it would be very much easier for the pilot to maintain an economic cruising mixture with the compression ignition engine than with the very complex system of controls which had become necessary with the petrol engine.

Commenting on the table in the paper showing the comparison of 1,500 b.h.p. air-cooled radial engines (100 octane and compression ignition), Major Mayo pointed out that the two cases dealt with were based on engines of the same maximum power, and that they were given the same cruising power for comparative purposes. But just above the table it was stated that it was practicable to take a higher percentage cruising output, from a given size, from the compression ignition engine. It was a point to be borne in mind, continued Major Mayo, that apart from the very substantial advantage in cost, the compression ignition engine offered on a comparative basis a somewhat higher cruising speed, if one wanted to realise it, because one could run the engine at a higher proportion of its maximum power.

Putting in a word for the smaller sizes of engine, he said they were being neglected at the present time, the reason being the urgent need for military engines of much larger size and the consequent difficulty which the industry experienced in developing engines for civil purposes. The fact was that there were considerable gaps in the range of engines available for civil and commercial aviation, and he felt that some measure of support might well be accorded by the Government to prevent a serious lag in that direction. He asked Mr. Fedden why he foresaw the possibility of developing the compression ignition engine only in the larger sizes. It seemed to him personally that there would be very great advantages in using the compression ignition engines of comparatively small sizes, especially for the smaller commercial aircraft and private aircraft.

He thought that many of the advantages which had been mentioned specifically in the paper in regard to large engines would be of particular importance in the smaller sizes of engines for private and commercial aircraft.

Mr. A. E. L. CHORLTON (*Fellow*): He was a little puzzled as to the reason why the period of prophecy was limited to five years. What was peculiar, he asked, about the period of five years, which period was so frequently chosen? Had Mr. Fedden visited Russia? It was a little disappointing that Mr. Fedden had not given more details of the engines referred to in the paper. It was rather remarkable how the internal combustion engine for use in the air seemed to be reverting to the designs of the old days. Some of the latest engines were of the slide valve type, and the ignition was reverting to the old type used in slide valve engines long before the war, where the projecting plug was dispensed with entirely and the ignition was carried in a pocket in the valve itself. What sort of development did Mr. Fedden foresee in designs such as that?

Mr. Chorlton was also very greatly disappointed that the compression ignition engine had not progressed faster than in fact it had. Of course, he realised that the development of the high octane fuels was an important reason, and one could not escape from the position that in all probability such development would continue and the cost of the fuels would tend to fall. So that unless something much more vigorous was done in the future than was being done by the Government at the present time, the compression ignition engine would seem to have a very poor future indeed, for aeronautical use. It had been a constant puzzle to him that precautions were not taken to ensure that that engine was pushed along, at any rate to exhaust its possibilities, and that provision was made against any eventuality in the future. Year after year he had asked questions in the House of Commons on the subject, but had received no sort of reply, and he was convinced that no action would be taken until a body of the standing of the Royal Aeronautical Society got on to its hind legs and demanded that something should be done.

Mr. C. P. LIPSCOMB (*Associate Fellow*): He expressed his firm's keen appreciation of Mr. Fedden's efforts in the development of air-cooled engines and said that his work had done much to place this country in the position it occupied in regard to aero engine development. Mr. Fedden had asked, he said, for a lead from the aircraft designing firms, but it was almost as difficult for them as for him to foresee developments over the next five years. One sympathised with Mr. Fedden because, whereas the development of an engine involved four or five years' work an aeroplane could be designed in about half, or less than half that time.

Mr. Lipscomb confessed that he was rather frightened by the suggestion to place six or eight engines along the leading edge of a wing, particularly in view of the fact that nowadays wing loadings were tending to increase more and more and might even reach 50lbs./sq. ft. He wondered what would be the spoiling effect on the wing with a number of engines spread along the leading edge, also the effect of the outboard engines being well out towards the wing tip.

In considering the grouping of engines or their location in single units consideration would have to be given to the airscrew question. For commercial aeroplanes he believed that it would be agreed that from the noise point of view it is desirable to limit the cruising tip speed to a maximum of 800ft. per sec. and probably less at high altitudes. He had roughly calculated the size of airscrew required for a flying boat cruising at 200 m.p.h., with a 2,000 h.p. engine. In order to limit the tip speed to 800ft. per sec. at 5,000ft. it would require approximately a 17ft. diameter airscrew rotating at 840 r.p.m., with engine r.p.m. of 2,400. For take-off it is permissible to increase the tip speed to about 1,000ft. per sec. which would result in the engine r.p.m. being increased to about 3,200.

It is doubtful whether such a large increase in r.p.m. would be permissible, and therefore serious consideration would need to be given in the case of the

2,000 h.p. engine for the incorporation of a two-speed gear. As engine powers increase still further the two-speed gear would become more necessary.

He said that the foregoing remarks only applied to aeroplanes operating under their own power and did not necessarily apply to those with assisted take-offs.

His firm as flying boat constructors had no objection at all to the use of the compression ignition engine provided the take-off conditions could be met.

For flying boats with an unassisted take-off it is essential that the highest possible thrust be obtained during the take-off run which may be a disadvantage of the C.I. engine. Undoubtedly the C.I. engine has many advantages when long ranges are being considered, not the least of which is the reduction in fuel capacity required and therefore every encouragement should be given to its development.

Mons. MÉNÉTRIER (Chief Designer, Moteurs Potez, France): A paper by Mr. Fedden is a much awaited event, not only in his country, but also among the aero engine technicians of the world. A remarkable feature of British character is, in his opinion, a definite ability to compromise between the desirable stability arising from the lessons of the past and the necessary changes imposed by the trend of the future. This ability is, he thought, best represented by Mr. Fedden and he was thankful to the inspiration that led him to attend this meeting to-night and hear the paper directly from its author.

Mr. Fedden has stressed the great amount of time and painful work necessary to carry a new design to completion and in this respect he wished to emphasise the necessity of observing, as regards aircraft engines, the law of continuity.

Regarding the present two lines of design, *i.e.*, single or dual row radial, and single or multi-banks in line engines, it may be useful to look back to old times and remind them that so far as 1911 they had in France two well-known air-cooled stationary engines: the Anzani single and double row radials, and the Renault V8, with incorporated fan cooling and baffles. He thought that if circumstances had allowed, and if their constructors had had the sense and possibility to observe this law of continuity in design, they might have disposed five years ago of the engines they would have five years hence.

The two types of engines, radial and in-line, have definite advantages and limitations in particular as regards cooling. The radial allowing for a better finned head, but requiring complicated baffling and large frontal area, and the in-line imposing a more restricted finning to be compromised with a reasonable distance between cylinder axes, while allowing for simpler baffles and low frontal area.

In order to compare the two, he thought it might be interesting to test cylinders of each type having same bore and stroke, on single cylinder testing units consisting of exactly the same parts, including piston, etc.

These tests would still be more valuable and the general research facilitated if the same type of single cylinder testing unit could be used in different countries.

As regards the Potez flat 12, he expressed his satisfaction to have heard Mr. Fedden speak favourably of this type for the lower power class.

As a return to the substantial subject of study presented by him in his very interesting paper, he would like to give a few particulars about this engine that may interest the audience.

The design was established in close co-operation with the aeroplane technical department of his company, and chosen after extensive comparative wind tunnel tests of three types: the double bank radial, the V12 inverted and the 12 flat. Although the differences in results were not very great as might be expected they found definite advantages in favour of the last as regards drag, ease of cooling and accessibility.

Furthermore, tests on a single cylinder unit have shown them that the "in-line" type of cylinder chosen will sustain 14.5 k/cm.^{2} (208lbs./sq. in.) b.m.e.p. with 1225 m/m. Hg. and 100 octane fuel quite normally with a cooling air delivery of only 7.5 gramms per h.p. per sec., which compare equally with

the performance of a "radial" type cylinder of similar capacity. The above figures correspond to 43 h.p. per litre at moderate speed, thus bringing the complete engine within the power given by Mr. Fedden for the first of his four categories.

The low weight of this engine, referred to by Mr. Fedden, is due mainly to very careful consideration of fatigue stresses of parts, to a short stroke and to the adoption of through bolts connecting the heads of opposite banks, thus relieving the magnesium crank case of high tensile stresses.

It should be noted that the weight of the present engine includes a reducing gear which can be suppressed on certain aircraft, thus reducing simultaneously the weight by about 17 pounds and the frontal area.

The width of the engine is only 37.5 inches and the whole engine can be, in its present state of design which is not, as yet, intended for a pure "wing engine," inscribed in a 31.5 inches diameter circle with only a small boss protruding on each side.

The length is considerably reduced by adoption of an underside supercharger and the accessibility on the aircraft rendered very good by elimination of rear crowded accessories.

Every design has, of course, its limitations and in this respect it must be recognised that the flat twelve should, on account of inertia torque which compares with that of a 6 in-line of much higher bore and in order to retain the simple 6-throw crankshaft, be designed on a basis of moderate piston speed and high mean pressure, the facilities in cooling offered by this layout allowing for an increase of the latter.

Major CARTER (*Fellow*): With reference to the problem of weight in relation to size, Mr. Fedden had given a weight of 1.1lb. per b.h.p. for his 700 h.p. engine and 1lb. per b.h.p. for the 1,500 h.p. engine, so that the smaller engine was the heavier per b.h.p. It was well worth considering the dimensional law, because if engines were made faithfully to the drawings but scaled down in size, the specific weight would bear the same proportion to the linear dimensions for all sizes. The dimensional theory had been very unpopular because it had meant that as engines became larger the problem of limiting the weight became increasingly difficult, but the specific weight of the engines had not increased in proportion to the increase of power, by reason of improvements in technique and in the fuels used. Was there not a real possibility of scaling backwards to the smaller engine and producing small engines whose weight would bear still smaller relation to the power developed? For example, theoretically, if one worked on the drawings of a 1,600 h.p. engine, weighing 1,600lb., and produced an engine of half scale and of twice the r.p.m., it would give about 400 h.p. and its weight would be reduced to about 200lb., that is, to ½lb. per b.h.p. It was true that magnetos and sparking plugs could not be scaled down, but a factor operating in the opposite direction is that cooling conditions would be better in the smaller engine. The gain was so large that extra weight could be allowed in places and the specific weight would still be low. All speeds, stresses, bearing loadings and relative values of vibration frequencies would be the same as in the prototype engine. He would need some convincing that the practical difficulties were preventing developments in that direction.

M. JEAN PONTREMOLI (*Fellow*): He still thought that engines now launched for production and which one considers as having a comparatively high horse-power and rating, will in a few years' time, as has happened before, be also further increased in power and that they would again have to step up the output. This will not be as the necessity arises, but as improvements in technique will allow.

As regards the installation of big engines on the wings of machines and the necessity for engines being comparatively widely spaced, due to the large airscrews and the very low reduction gear ratios, this point is of so great importance that he thought much work should be done quickly to further investigate the

possibility of using smaller airscrews turning at higher tip speed than sound speed. It seems very possible that the actual limit of the sound speed only holds good for existing types of blades, but new designs might be investigated which would keep good efficiency at a higher speed. This, of course, would be to the common benefit of the aero engine maker and the aircraft designer.

Referring to the four categories of engines suggested by Mr. Fedden, he really thought the use of 300-400 h.p. engines in multi-engined military machines would become more and more important, and that this size should not be overlooked, two of these engines superseding the old type of single-engined machine of about 450-500 h.p. On the other hand, it is very likely that much time will elapse before the use of 2,000 h.p. engines will be wanted, and he was not sure that before that date the trend of aircraft design will not call again with preference for smaller engines.

As regards fuels, he was still wondering whether the 100 octane fuel is a necessity, or if they would not be able to improve the combustion quality of the cylinder and increase the compression ratio to reduce consumption and the heat losses, and still use for a long time a fuel of 87 octane. To a certain extent, improvements in lubricant qualities seem to me to be very important at the present stage of the aeroplane industry.

He was very interested to see that now Mr. Fedden looks with much interest in the direction of the compression ignition engine, which has been much too much cast aside, but Mr. Fedden thinks that the compression ignition engine is only worth considering on a fairly large size engine of not less than 1,000 cruising h.p. This does not agree with the writer's opinion, and for many reasons he thought that the smaller sizes are still more interesting and that as soon as possible all the private machines and trading planes should be fitted with these engines, were it only because many more people would like to fly if they had no fear of fire risk, and certainly insurance companies would provide specially reduced rates for machines so equipped. Also on these machines the weight is not so important as economy in fuel.

He would like to see a date officially announced on and after which no petrol engine would be allowed to fly on this type of machine.

Mr. Fedden's remarks regarding the falling air temperature with altitude offsetting the effect of the reduced air density are very interesting and he would like to know what is the exact value that they could attach to the equation shown.

In another part, Mr. Fedden says he thinks that the importance of the small diameter of an engine has been overestimated in connection with aircraft. The same remark has been made to the writer by another engine designer. The opinion was asked of four different aircraft designers who were all very strongly in favour of the smallest possible diameter for most types of machines, information which does not seem to concur with that of Mr. Fedden and Mr. Barnwell.

He was quite in agreement with Mr. Fedden's wish to be able to standardise a four-point fixation for interchangeable types of engines. Many individual efforts have been made in this direction, but will be unsuccessful so long as the aircraft builder will not agree to standard compromises, and the sooner such a decision is arrived at, the better it will be for the ease of aircraft maintenance.

As regards the small radial engine, it was obvious at the Paris Salon that in every respect the installation of the radial was much neater and much simpler than the " V " type on any multi-engined aircraft, and on this he agreed with Mr. Fedden that if the air-cooled in-line engine has a market, it will be of the " flat " and not " V " type.

Mr. S. H. Evans (*Associate Fellow and Member*) : The lecturer had presented such an impressive case for the single-row radial that it would be difficult for the aeroplane designer to state a case for the twin-row or multi-bank in-line types. However, he felt that the majority of designers were attracted to the advantages of small frontal area as against the claims of increased wetted surface, although he agreed that in the case of the very large wing installations which we were now

approaching, there might be little to choose between them. For single-engined machines, he believed that large diameter engine cowls were a serious handicap, not only aerodynamically, but in relation to the pilot's forward vision. There was also the question of propulsive efficiency to be taken into account, since the finer nose possible with the twin-row and in-line types might be expected to improve the combination to some extent.

On the subject of airscrew interference and the best position for an airscrew located ahead of the leading edge, he noted that in Sect. 6(b) of the paper the familiar N.A.C.A. figure of 30 per cent. of the wing chord was cited as a minimum. In the next paragraph, however, the figure of 10 per cent. is stated as not appreciably affecting the propulsive efficiency. As wings grow larger, the idea of burying a radial engine completely in the leading edge and ducting the airflow to the trailing edge was an attractive thought to the aeroplane designer, but the proximity of the airscrew disc to the leading edge was rather worrying him in connection with the Burnelli principle at the moment. About ten years ago the Engineering Division of the U.S. Air Corps investigated the effect of placing the airscrew close up to a large wing and the results (given in N.A.C.A. Technical Report No. 235, " Interaction between Air Propellers and Airplane Structures," by Durand) indicated a serious drop in efficiency if the airscrew approached closer than about 20 per cent. *of its diameter* to the leading edge. Even the latter position resulted in a loss of about 4 per cent. in propulsive efficiency, so perhaps Mr. Fedden could tell them whether the Bristol Co. had some more recent information up their sleeves on this point because he felt sure that the aeroplane people would welcome it? In certain cases, of course, Mr. Fedden's figure of 10 per cent. *of the wing chord* might agree with Durand's experiments where the efficiency losses have been plotted against the distance from the leading edge expressed in terms of the airscrew diameter rather than the wing chord.

He confessed he was disappointed to see the weight figures on the Bristol twin-row radial of 1931, because from the illustrations this engine looked like a very nice aerodynamic proposition. At the same time he much admired the lecturer's frankness in showing them its weaknesses because that showed the real engineering spirit. Moreover, he was gratified to think that Mr. Fedden had given this country a very definite international lead with his latest twin-row sleeve-valve design, a design which impressed him very much indeed. The lecturer had been generous enough to pay his friends of the Douglas Co. a very pretty compliment in describing their work as a classic example in aircraft fashions, and he was sure that they would be the first to reciprocate by acknowledging Mr. Fedden, not only as a classicist in the development of radial air-cooled engines, but a thorough-going modernist at the same time.

(*Communicated.*) With reference to Mr. Fedden's lecture given on the 18th of February regarding " The Trend of Air-Cooled Aero Engines—the Next Five Years," and further, to the verbal discussion following the lecture, he would like to add one point concerning Mr. Fedden's figures which he did not fully appreciate until the tables prepared by Mr. Fedden were published.

Referring to the table giving engine comparison on the basis of British horse-power per square inch of piston area, the figures taken for the several engines do not seem to be quite correct.

The discrepancy has very likely resulted from Mr. Fedden having taken the maximum power of some of the engines and for other engines, the rated power, as used on the Continent and in the United States, the latter being very different from the maximum ratings.

For example, the maximum rating for the Wright Cyclone, Gnome Rhone and Hispano Suiza engines would all be between 10-15 per cent. higher than the figures quoted in Mr. Fedden's table.

This, of course, completely changes the figures in all the columns.

For two engines the figures quoted as maximum power are even lower than the actual rated power, which are, of course, again much lower than the actual maximum power.

In conclusion, if the figures for all the engines had been taken under the same conditions, the conclusions drawn by Mr. Fedden must certainly have been very different, as well from this more accurate table as from the other showing relative merits of various air-cooled engine layouts.

Mr. BAXTER: With reference to Mr. Fedden's advocacy of fitting an engine close to the spars on a wing, and to a short shaft drive, he said that at one time there was a very strong impression in the aircraft industry that the shaft for airscrew drive was a completely impracticable proposition. Therefore, he asked what additional weight was involved by the adoption of an extensive shaft drive and what difficulties were involved in connection with the necessary flexible connections.

Mr. A. J. ROWLEDGE (*Fellow*) (*contributed*): He was glad to see the author putting in a plea for further work on the compression ignition type of engine, which he thought was being too much neglected by them at the present time. He would like to offer one or two remarks, more particularly with regard to what the author calls "Engine Layouts from the Geometric Aspect." When he states the horse power per square inch is a better comparison than horse power on a capacity basis, he was quite in agreement with him, but the author must make allowances for the stroke bore ratio or otherwise only compare similar engines. This is shown clearly by the "Pegasus" and "Mercury" engines.

He did not agree with the author's conclusions as regards the effect of the size of cylinder on the horse power weight ratio. He thought it would be found that the smaller cylinder is lighter, but as this point has been thoroughly discussed in many papers he would leave it at that unless the author was prepared to give them some detailed figures to discuss.

He also thought the author over-estimates the weight of the in-line type of engine.

He would suggest that the "Cross" type of engine has considerable advantages in general layout. It is very convenient, as the intake for the cooling air can be conveniently placed, to obtain advantage from the slip stream on climb, plenty of room is obtainable for adequate air passages and the exhaust pipes come in very conveniently, and the cooling air does not pass over these pipes until it has done its work in cooling the cylinders.

The radial type of engine does not show up as well on either the air intake or the exhaust pipe arrangement.

Again, with regard to the best size of cylinder, he would suggest that the higher b.m.e.p. which they expected to use to take advantage of better fuel would reduce the maximum useful size of cylinder.

He would have expected to see more reference to pressure cooling, and he suggested that in the next five years tests of cylinders running in a free air stream will be forgotten, and that they would return to the conceptions laid down by Dr. Lanchester many years ago when considering the question of the air-cooled cylinder.

Mr. L. KEULEYAN (*communicated*): In his paper Mr. Fedden indicates very clearly his growing belief in the future of the C.I. engine, particularly in the high powers, and points out the many advantages of such engines from the point of view of reliability and cheap range of flight in which he was quite in agreement.

He would like, however, to comment on the taken comparison of 1,500 b.h.p. 100 octane and C.I.

Referring to specific output, Mr. Fedden seems unaware that German engineers are now actually getting 42 h.p./litre and expect to attain shortly about 50 h.p./l., which is not certainly obtained at present, even in high efficiency racing engines with 87 octane fuels.

Further, he did not agree with the author's estimate of net dry weights for the two types of engines which, to his mind, should be much more nearly comparable, namely, 1,620 and 2,100lbs.

His own experience with 8 and 36 litre engines operating with 0.500 and 0.700 atmospheres supercharger pressure and using 87 octane fuel is that peak pressures are over 80 atmospheres at the point of ignition; with 100 octane fuel, these pressures will be considerably increased due, of course, to the increased compression ratio used for higher output.

Mr. Fedden is no doubt aware of the experiments carried out at Farnborough by Mr. Taylor, he believed on the 20T. engine where peak pressures did not exceed 50 atmospheres, and he did not see why these pressures should be exceeded on well designed C.I. engines, as recent experiments have shown that peak pressures in C.I. engines will be considerably less than those necessary for the same specific output in 100 octane or iso-octane engines. If the latter are to have the same mechanical reliability their weight must be similar, if not greater, than those of C.I. engines.

Capt. R. W. A. BREWER (*contributed*): Discussing Mr. Fedden's conclusions first, the statement "the general trend to submerge power plants entirely in the wings" is very logical and in accordance with what other thinkers have advocated. The Fokker thick wing lends itself to the inclusion of the radial engine. His first project on joining Mr. Fokker as mechanical consultant in 1928 was to design for the F.32 an arrangement of four Hornet engine mounts, cowlings, and air baffles, so that this could be done. The requirements were that the engines should be arranged in tandem, one tractor and one pusher with shaft drive. They were mounted one on each side of the front main spar, the wing chord being 204 inches.

At that time the Pratt and Whitney engineers were astonished that he would wish to attach anything to the nose of an engine, as was desirable in this installation. Probably in view of the research of the N.A.C.A. this would not now seem unfavourable, as, for instance, an extended nose. They did not then have any data as to the best position of these units, nor as to propeller location relative to the leading edge of the wings. For this reason the N.A.C.A. was asked for guidance.

Looking over the layout, it appears even now to be quite logical. Sufficient it is to say that Mr. Fokker's idea at the time was very sound and could have been put into practical usage in the F.32. The next step taken would come under Mr. Fedden's interpretation (1) of "the wing engine requirement" and he coupled a comment under his "standardisation of power units," section 7.

When the project of the wing engine was outlined to the writer by Mr. Fokker in 1929 the conditions laid down were very similar to those stated by Mr. Fedden. From the point of view of the aircraft designer and manufacturer the following outstanding sources of expense and nuisance were very apparent at the time.

(1) The bare engine, as to cost and work involved, is only a part of the story.
(2) Mounting the said engine in an aeroplane was a very different problem from mounting the same engine in a test stand in the engine factory.
(3) Some engines offered were almost impossible to mount in a plane at all, or to make even partially accessible.
(4) An engine when mounted on the type of structure in vogue required a mass of subsequent work before it became an operable unit.
(5) Tanks, pipes, wires, accessories of many kinds had to be provided and attached where possible in the "no man's land" between the engine and the pilot.
(6) Servicing such a collection of material was usually a lengthy, difficult and expensive undertaking.
(7) The power plant had no unity.

Mr. Fedden's recommendations of a standardised power unit is just exactly what they aimed at, and during 1929 and 1930 several such engines, known as the "Gryphon," were made. Larger types were subsequently designed because it was found that the smaller machines did have merit and could be made at a reasonable cost.

The Gryphon engine is of cantilever construction mounted on the fire wall by six bolts. Mushroom feet with rubber pads arranged symmetrically about the centre line of the crankshaft permit what is now known as "floating power." The requirement laid down by Mr. Fokker was that the engines should be able to run in any position, should be capable of full power take-off at either end of the crankshaft, should be complete with cowling, oil tanks, and all accessories. Engines must be mountable in the wings as twins, or/and vertically in the nose for three-engined or single-engine installations. In actual fact this was carried out, but for the larger units a remote geabox is preferred. The power plant is removable as a unit.

Mr. Fedden's suggestions had been met in the U.S.A. seven years ago. All that is now needed is extended development of the type into larger units. This can be done without producing a prohibitively costly machine.

The statements as to the need of what Mr. Fedden calls a "specialised type of engine" are well taken. His comment is only that the required engines are specialised in so far as being different from what have been developed into highly efficient standardised types in several countries. Perhaps it may be "better business" to develop planes to suit available engines, as in the past, but he says "the day of the general purpose engine, except for certain civil aircraft requirements, is fast disappearing."

He agreed.

Reply to the Discussion.

Mr. Fedden, replying to Mr. Banks' criticism that he had been a little unfair to the 100 octane petrol engine, said he had given a figure of 0.43lb. per b.h.p. hour because his figures were based on the high cruising power of 66 per cent. of the maximum power (not 66 per cent. of the normal power), and that was a good deal higher than we were accustomed to use in air liner work. Although the fuel consumption figures for the petrol engine might have been a little high, the figures for the compression ignition engine were also equally conservative. The figure of 0.38lb. per b.h.p. hour was actually obtained on the Bristol Phœnix for a considerable period of cruising, by the Westland Company. In the recent classical paper on the Junkers, by Doctor Gasterstadt, figures as low as 0.35lb. per b.h.p. hour were given.

With regard to the effect of air density on cooling, he said he had seen the paper by Mr. Taylor on "The Next Five Years in Spark Ignition Aviation Engines," and he felt that the best answer to Mr. Banks was that, if one got busy with figures on such lines of investigation, without wishing to give offence to anyone, he believed one could "make the punishment fit the crime" in whatever way one chose. The slide he had exhibited in connection with that matter was prepared from results obtained on a single cylinder, unbaffled; and where it was stated that the cooling power loss varied inversely as the 9th power of the temperature difference (equation 2) he considered that it might justifiably be modified to the 6th power if one considered the very latest edition of cylinder, fully baffled. His company had lately had some experience of high altitude flying, and, contrary to their expectations, they had not experienced trouble with cylinder temperatures at altitudes of approximately 50,000ft. He assumed that, at any rate for regular long-distance flying, some time would elapse before machines would operate at heights in excess of 30,000ft.

Replying to Major Green, he said that aerodynamic experts had told him that tests must be carried out either in the air under full-scale conditions or in a wind

tunnel having a high wind speed. On the occasion of the last Paris Salon he had visited the Hispano Works and had been impressed by the fact that an engine firm had had enough initiative and drive to provide a 26ft. tunnel in which a wind speed of 214 m.p.h. could be attained. He imagined that the results for which the industry was looking would be a good deal more interesting if tests were made in a tunnel in which such a high wind speed could be attained; but he was not really competent to express a definite opinion on this matter.

The Rolls-Royce and Bristol Companies had carried out some considerable work on compression ignition aero engine research, and had achieved a certain amount of success. But, speaking for the Bristol Company, he said that the chief trouble was that they had always had to make compression ignition the third or fourth priority. In his opinion general aero engine builders, who were trying to do research or development work on the compression ignition engine, never really devoted sufficient time to the problem on hand to realise complete success, for they were frequently called upon to turn their experimental resources to some pressing trouble which had arisen in current petrol engine production or to some other more immediate problem; and in his view compression ignition research ought to be tackled by a separate specialised concern. The petrol engine had become such a terribly spoiled child of late years, and everything had been given over to it. Research on petrol and allied fuels generally had given the petrol engine such an advantage, and compression ignition development had never been conducted with the real drive that was needed to give it a chance to come into the picture, and he felt that unless this were remedied and the problem tackled by someone having no outside interests, there was little chance of real success.

Welcoming Major Mayo's remarks, he said that the Bristol Company valued greatly the information derived from the use of their engines by Imperial Airways, and the development resulting therefrom. Imperial Airways were hard taskmasters, and the Bristol Company had to watch their step when they put on to an Imperial Airways service an engine which had been developed for military purposes. Quite frankly, there was no real civil engines in the larger categories to-day. The big engines were always military types, and, when his company had completed the work they might have to do, to the requirements of the Air Ministry, and had obtained good results from these engines for military service, Major Mayo and his engineers usually found some trouble! Nevertheless, the use of the engines by Imperial Airways was of great value. He agreed with Major Mayo's remarks concerning the gaps between sizes of engines, but he was afraid that that was an exigency of present conditions. There was an excellent range of the smaller sizes of engines specially developed for civil work, as, for instance, the De Havilland, but there was nothing between these and the big military engines. A few years ago the Bristol Company had developed a 15-litre engine in an attempt to fill the gap and to compete with the very excellent American engines of that category, such as the Wasp Junior, but the company had had to drop that work for the present, although he hoped they would be able to come back to it when conditions became more normal.

Dealing with the question as to why he felt that the compression ignition engine had a better chance to compete with the petrol engine in the larger than in the smaller sizes, he said there were three main reasons. In the first place, the accurate measurement of a very small quantity of fuel was a difficult problem, and, therefore, he would not like to have to think of obtaining reasonable combustion in cylinders of less than about 5in. bore, judging by the Bristol Company's experience. Secondly, it was more difficult to compete in respect of weight in the smaller than in the larger sizes, because, owing to scantlings, more weight had to be used to deal with the higher explosion pressures of the compression ignition engine. Thirdly, owing to the more severe torque of the compression ignition engine for a given power, it was necessary to provide more cylinders for a given swept volume. In other words, if one considered, for instance, a classic

type of petrol engine of 100 to 120 h.p. employed for civil work, he felt that, when working on the compression ignition principle, it would be necessary to use more than four or six cylinders in order to obtain equal results. Therefore, he considered that the compression ignition engine had more chance of competing with the petrol engine in the larger sizes. Although he agreed that endeavours should be made to develop the compression ignition engine in smaller sizes, he had a hunch that the problem would be successfully tackled first in the larger categories.

Commenting on Mr. Chorlton's query as to why the period of prophecy covered by the paper was limited to five years, Mr. Fedden said that prophecy, in any branch of engineering and especially aviation, was extremely rash, and he thought that probably he had chosen the period of five years because it was a short time relatively with which to get into trouble, and it was about the time necessary to develop a new type of engine.

Dealing with the question of why the compression ignition engine had not come to the front ere now, he said that so long as people persisted in the attitude that compression ignition engines would be used for aircraft as soon as they were equal to the petrol engine in all respects, we should never use them. He was not satisfied to hear aircraft designers say that they had no objection to the compression ignition engine, but he wanted them to feel, as he did, that in certain categories of aircraft the advantages of the compression ignition type of engine were so great that they were prepared to give away something in favour of the new form of power plant while it was "feeling its feet." If they would be patient for a few years and give the compression ignition engine a chance to come into its own, he was certain they would be surprised and pleased by some of its characteristics.

Replying to Mr. Lipscomb, he said he was hoping to secure advice on the subject of the number of engines that could be used on the leading edge of a wing. He felt it was desirable to keep down the size of the power unit as much as possible. In view of Mr. Lipscomb's remarks concerning the propeller problem, it seemed that we must meet it either by a two-speed reduction gear or twin concentric propellers. He felt that the assisted take-off type of aircraft offered the compression ignition engine the best chance of making good, because that engine was rather less sensitive to rich mixture and over boosting than was the high octane petrol engine, but, on the other hand, it could be cruised at nearer its normal output.

When he had chosen the flat Potez for illustration as one of the most interesting engines shown at the recent Paris Salon, he had had no idea that Mons. Ménétrier, the designer of it, would have honoured the meeting by attending. He appreciated very much the fact that Mons. Ménétrier had gone to the trouble of coming over from France and taken part in the discussion. At the same time, he did not agree altogether with Mons. Ménétrier's views concerning the early development of in-line engines such as the Renault. Undoubtedly, that type of engine had been interesting and reliable in its day, but the radial had beaten it on all counts—not only on weight *per se*, but on the general effect of drag in relation to weight.

The question put by Major Carter of endeavouring to scale down an aero engine had been asked him frequently before, but he was afraid he had always failed to answer it completely. All that he could tell Major Carter was that the tabulations he had shown were honest and genuine data. Further than that he could not go, and he must counter this argument by pointing out that it was not practical to scale down an engine in size and weight exactly, for the carburettors, magnetos, and plugs, for example, weighed the same whatever the capacity of the engine. The connecting rod of a motor bicycle engine, for example, was just about the minimum thickness that could be stamped, and the whole problem of design and stressing of such a component was very different as between these small engines and a large aero engine. For instance, if the

28-litre Pegasus engine were scaled down to 4-litre size and the scantlings reduced irrespective of the strength and modulus of the different materials, there would be, in some components, sections of approximately paper thickness, which were just unproducible.

Mr. Fedden agreed with Mr. Pontremoli that progress had been made in increasing the power developed by engines of a given volume during the last few years, and he thought that we should make still more progress along these lines. For example, about six years ago one of his company's 25-litre engines had developed 480 h.p. at 15,000ft., whereas to-day the same size of engine was developing 820 h.p. at 13,000ft. at powers approximating 1,100, and with the supercharger opened out to full capacity on the ground made possible by the use of special fuel. This same engine had lately been run for considerable periods, and, though not entirely without giving some trouble, within two or three years such difficulties would be overcome and a still higher rating obtained. But he did not agree that we should not use 100 or even higher octane fuel, at any rate for military machines, if the fuel suppliers were prepared to provide such fuel in reasonable bulk. He believed that we should improve the technique of our engines, that we should find better bearing and piston materials, and that we should learn how to run engines faster on the present fuels; and then we should go on to use better fuels. For example, if we could obtain 1,000 h.p. from a flat engine of approximately 3ft. long, fitted completely inside a wing, then in his opinion it would be worth doing so for the super military machine, no matter what it cost.

With regard to Mr. Evans' remarks concerning propellers being located at 30 per cent. and 50 per cent. of the chord ahead of the leading edge of the wing, he believed that research work at the Royal Aircraft Establishment had shown that 30 per cent. ahead was the most efficient position for a normal wing in conjunction with a radial engine. Nevertheless, these far forward positions were employed also for engines for the purposes of aircraft balance and for convenient housing of the undercarriage, and his company had certain machines in course of construction, with their new type engines, in which they were going as far as 45 and even 48 per cent. When he had referred, in the paper, to the propeller being 10 per cent. ahead of the leading edge, he had visualised using engines buried inside the wing. He had nothing up his sleeve about that, but he hoped that somebody else had, because if the flat engine were as important as he believed it to be for the fighter class of aircraft, much would depend upon whether or not the propeller could be located as near as 10-15 per cent. of the chord in front of the wing without loss of efficiency and without giving rise to trouble with the engine or the wing.

Replying to the comments made with regard to the octagon double-row radial of 1931, Mr. Fedden said he had illustrated that engine in order to emphasise that one could not afford too many cylinders for a given volume. The engine had been quite successful from the functional point of view, but it was too heavy. It was a high speed engine and it had been necessary to put a great deal of stiffness into it—and this fact, combined with overhead camshafts, had conduced towards the power/weight ratio being unsatisfactory. But he did not think we need to fear in respect of the power/weight ratio of the modern vintage of double-row British engines; he believed we had double-row engines which were as light as the American types and having power outputs as good as or even better than the American engines, although we had not possibly so much experience as had the Americans on the production of this series.

Dealing with Mr. Baxter's comments on his statement about engines buried in the wing necessitating the use of separate propeller shafts, he said that in the design which he had suggested he would not propose using a separate shaft; but nevertheless he did not think it was impossible to use separate propeller shafts successfully, although the weight factor might be serious. The Parnell machine, with the Napier Lion engine, had had separate propeller shaft drives

which were quite successful; and the Bristol Company had designed and made, about 1922, a four-engined machine with separate propeller shaft drives, using the Puma engines. The transmission in both aeroplanes was quite successful, and he believed that the achievement of satisfactory results was purely a matter of understanding the technical problems of the propeller shafts and engine crankshafts.

On the motion of the PRESIDENT, a hearty vote of thanks was accorded Mr. Fedden for his paper.

COMMUNICATED REPLIES.

Mr. A. J. Rowledge (Rolls-Royce, Ltd.).—If one agrees that, for fairly large variations in stroke, piston speed is the main factor governing rotational speed, then stroke bore ratio need not be considered when comparing engines on the h.p. per square inch of piston area basis, since, for a given bore, port areas can be arranged to deal with a given swept volume per minute, which itself is a function of piston speed and irrespective of stroke. It is felt that this argument is borne out rather than contradicted by the comparison of Pegasus and Mercury, for it will be noted that, if the piston speed of the latter is increased to that of the former and the power output stepped up accordingly, the b.h.p./sq. in. of piston area would be the same for both types.

With regard to the " Cross " type of engine, it is agreed that this type has considerable advantages in general layout, but it is maintained that it is bound to be heavier than the radial of comparative capacity. For the larger sizes necessitating the use of 24 cylinders it is undoubtedly attractive.

Mr. Jean Pontremoli.—The figures quoted for the Gnome-Rhone, Wright Cyclone, and Hispano Suiza engines were the latest available, and are based on figures quoted in the Paris Show reports, the figures for the two latter engines being quoted as maximum powers at altitude. The Gnome-Rhone figures are given as normal ratings at altitude, but are the only figures available, and are understood to correspond to the English maximum.

Mr. Pontremoli does not give any figures for these engines, but even if those quoted in the tabulation are increased by 10-15 per cent., the conclusions are not affected. Furthermore, since the b.h.p./litre and b.h.p./sq. in. piston area comparison has no direct bearing on the relative merits of various air-cooled engine layouts (slide 13) it is not agreed that this slide will be affected.

Mr. L. Keuleyan.—The figures of 42 h.p./litre obtained in Germany refer to the Junkers 2-stroke C.I. engine. The paper compares only 4-stroke engines, since, at present, it has not been established that the 2-stroke is a practical proposition when employing air-cooling. If one considers the 2-stroke as a possible air-cooled type, it is agreed that the weights will compare much more closely with the 100 octane engine.

The question of high peak pressures is undoubtedly becoming of considerable importance on engines running on high octane fuels, and the danger of incipient detonation is well-known. Accordingly, the C.I. engine has an advantage in that peak pressures are controlled by the injection timing. The rate of pressure rise on the normal C.I. engine is, however, higher than on the petrol engine, and this has an important bearing on the fatigue stresses in the parts involved.

Captain Robert W. A. Brewer.—It is noted that Captain Brewer is in agreement with the author's views concerning submerged power plants, and the desirability for standardisation of complete power units.

Captain Brewer's remarks concerning the projected layout of the Fokker F.32 with 2 Hornets, one on either side of the main spar, are interesting, particularly in view of the objections which have been raised against the flat engine on the score of aircraft balance fore and aft. Mr. Fokker's requirements for full power take-off from either end of the crankshaft would, in the case of a radial engine, lead to a large diameter shaft being carried through the blower, with a consequent loss in efficiency.

AIRCRAFT PERFORMANCE ESTIMATION.

By C. O. Vernon, Stud. R.Ae.S.I.

(*Lecture read before the Students' Section on January 5th, 1937.*)

Almost the first thing anyone thinks of, when confronted with a type of aeroplane which he has not seen before, is its performance. He thinks, "What will she do?" This paper is an attempt to set out the methods by which the performance is estimated for a new design.

The subject has considerable scope, and only a certain portion of it will be covered here: Level speed and climb, range (at constant r.p.m.) and the take-off run.

Before anything can be done at all, something must be known about lift and drag, and something about airscrews. These will therefore be considered first.

Lift and Drag Characteristics.

The usual way of expressing the relative values of the forces acting on a body in relative motion with a fluid surrounding it is by means of non-dimensional coefficients defined by equations of the form

$$\text{Force} = C_F \tfrac{1}{2} \rho V^2 l^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where ρ = mass density of the fluid.
V = relative velocity.
l = some convenient length,
or alternatively l^2 = some convenient area.

C_F is called "force coefficient." Within certain limits, such a coefficient is constant for a body of any shape; it can be caused to vary, however, by a number of factors. The most important of these are:—

1. Vl/ν, or Reynolds number, where ν is the kinematic viscosity of the fluid.
2. α, or the incidence or inclination of some fixed datum on the body to the direction of motion.
3. The compressibility effect.

The variation of force coefficients with Reynolds number known as "scale effect" covers a considerable range; a large change of Vl/ν, however, is required to produce one of appreciable magnitude in the said coefficient.

The effect of incidence or attitude is large and cannot be computed theoretically; measurements must therefore be made over a range of values.

The compressibility effect is gauged by the ratio of speed of motion to the speed of sound. In ordinary flight it is negligible, since it only becomes of consequence when the ratio approaches unity. The point must be considered, however, when dealing with airscrews, since the speed of the blade tips may enter the critical region.

For ordinary flight, then, resolving the resultant force on the body into lift and drag, perpendicular and parallel respectively to the direction of motion, we can say that, over not too great a range of Reynolds number,

$$\text{Lift} = C_L \tfrac{1}{2} \rho V^2 A \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\text{Drag} = C_D \tfrac{1}{2} \rho V^2 A \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where C_L and C_D are lift and drag coefficients respectively and A is the area as represented in equation (1) by l^2.

The $\frac{1}{2}$ is inserted because $\frac{1}{2}\rho V^2$ happens to be the dynamic pressure or velocity head; the equations could then, if desired, be written

$$\text{Lift} = C_L qA$$
$$\text{Drag} = C_D qA$$
$$\text{where } q = \tfrac{1}{2}\rho V^2.$$

Some standard area must be chosen with which to work. For wings, the obvious one is the plane area, usually referred to loosely as wing area, and denoted S_w, so that we have

$$\text{Lift} = C_L \tfrac{1}{2}\rho V^2 S_w \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$
$$\text{Drag} = C_D \tfrac{1}{2}\rho V^2 S_w \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The lift of most parts of aeroplanes other than the wings is very small compared with the total lift; as a fairly close approximation, therefore, only the drag of such parts need be considered.

The question arises as to what area is to be used for defining drag coefficients. The one chosen need not, of course, be any particular area on the body itself; it can be any area, real or fictitious, whatsoever. When dealing with a body as part of an aeroplane, obviously the drag coefficient is best referred to the wing area, since the various component drags can then be summed directly.

The drag of individual bodies is often quoted directly, as so many pounds at a certain speed. This system could be used for drag summaries as it stands; there is, however, a very convenient alternative.

Instead of an area being chosen and the drag coefficient being based on it, the coefficient is fixed at an arbitrary value, say unity, and the area calculated which gives the correct drag for such a value, *i.e.*, denoting such an area by F,

Let $D = 1 \cdot \frac{1}{2}\rho V^2 F$ or

$$F = D/(\tfrac{1}{2}\rho V^2) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

F is termed the " drag area " of the body; for a particular aeroplane the drag coefficient is obtained by dividing the drag area by the wing area.

The skin friction alone, considered separately from any other drag of a body, is obviously proportional to the area exposed to the fluid; the resistance coefficient is therefore usually based on this " wetted surface " as it is called, *i.e.*,

$$\text{Skin friction} = C_f \tfrac{1}{2}\rho V^2 S_f \quad . \quad . \quad . \quad . \quad (7)$$

where C_f = skin friction coefficient.

S_f = total wetted surface.

The estimation of the lift and drag characteristics can now be considered of a complete aeroplane.

The drag may be divided into two main divisions—the induced drag, arising from a backward inclination of the lift due to the downward induced velocity, and the parasite drag which includes form drag, skin friction, interference, cooling drag, etc. With reference to wings the parasite drag is often called " profile drag "; this is a matter of terminology—any drag other than that directly due to the lift may properly be described as parasitic.

A summary of minimum parasitic drag is first compiled.

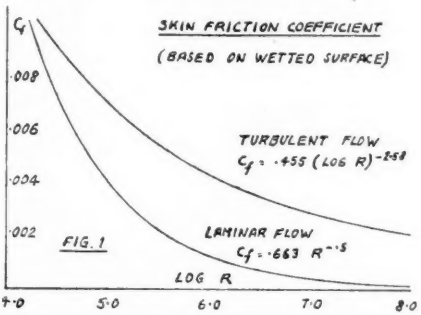
This consists of a tabulation of the minimum drag areas of all parts of the machine. The various figures are obtained either by wind tunnel tests on models of the actual components, or calculated from data supplied in handbooks or reports such as R. and M.'s, N.A.C.A. Technical Notes, and so on.

For the main items allowance is made for scale effect by calculating the model and full-scale Reynolds numbers, and reading the skin friction coefficients from the standard curve for turbulent flow, reproduced in Fig. 1, based on wind tunnel tests on flat plates at Göttingen several years ago.

The difference between the two values converted to drag area is subtracted from the model minimum drag, and the addition to this of a suitable allowance for such things as poor shape at windows, control surface gaps, etc., gives the full-scale minimum drag area.

Due to the use of fabric covering for the wings, for example, an increase in C_D of 0.0012 over a wing of perfect aerodynamic smoothness would be expected.

The engine drag is sub-divided into two parts, which are considered separately. The form drag, for single-engined machines, is taken into account with the fuselage, or for multi-engined types obtained by adding 70-100 per cent. to the bare skin friction of the nacelles, according to the " goodness " of their shape. For poor shapes, however, the drag might be considerably higher. The drag of cylinders or radiators, as the case may be, is usually reckoned as being equivalent to a certain percentage of the engine power at cruising or maximum speed



conditions. For past and some present-day aeroplanes the figure might be 10-15 per cent. or more. On future designs it is hoped, by proper design of cowls and ducts, to reduce this to 4-5 per cent.

The remaining small items, such as gun muzzles, aerial masts, etc., contribute only a small proportion of the total drag. It is sufficiently accurate, therefore, to treat these as cylinders, oval tubes, and so on.

The summary of minimum parasite drag is set out in tabular form; and example is shown herewith for an imaginary machine having a completely retractable undercarriage.

PARASITE DRAG SUMMARY.

Item.	Wetted Surface. sq. ft.	log R	C_f	F sq. ft.	Remarks.
Wings					
Fuselage					
Tail unit					
Loop aerial					
Nacelles profile					
cooling					
Tail wheel					
Total					

R in the above table stands for Reynolds number.

The variation of lift and drag with incidence is next considered.

The lift curve ($C_L \sim \alpha$) is first determined. Characteristics for the section chosen are obtained from a report dealing with wind tunnel tests on a family of such sections, such as R. and M. 1627 or N.A.C.A. 460. The values of α and C_L are usually quoted for infinite aspect ratio, and are corrected by standard aerofoil theory, for the actual aspect ratio used. The induced downwash α_i is given by

$$\alpha_i = MC_L/\pi R \text{ radians} = 51.3\ MC_L/\pi A \text{ degrees} \quad . \quad . \quad (8)$$

where A = aspect ratio or span^2/area.

M = a factor depending on the load distribution.

Then if α_0 be the incidence at a given C_L for infinite aspect ratio

$$\alpha = \alpha_0 + \alpha_i. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The value of α thus found is the actual one at which the wing must be set to produce the given C_L, and the α_0 is of no further interest.

The scale effect on lift is not such as to vary the slope of the lift curve or shift the no lift angle, but to extend the curve to a higher maximum as shown in Fig. 2. The full line shows the model values; the full-scale curve is the dotted one. The magnitude of the scale effect is a matter of some doubt; for design purposes it is therefore wise to assume a conservative round number value for C_L max. For the fabric covered wings of the past, which seldom had a good surface, a figure of 1.3 was considered generally attainable in practice; for modern wings with ply or metal skin, a higher value of 1.4 is justified. The final lift curve is given chain dotted on the figure.

The wing polar curve ($C_L \sim C_D$) is next drawn, based on the already determined C_D min. and C_L max., by analogy with the model curve, a constant C_D difference being applied for given values of C_L up to about 0.9-1.0, and the remainder sketched in to the same general shape, as shown in Fig. 3.

The induced drag is calculated from the usual equation, desired by aerofoil theory.

$$\text{Induced drag coefficient} = C_{oi} = NC_L^2/\pi A \quad . \quad . \quad . \quad (10)$$

N = a factor depending on the load distribution.

It is preferable to use " net " values of span and wing area, that is, excluding the part covered by the fuselage, for calculating the aspect ratio for use in the above equation; this results in higher induced drag than would be obtained by using the gross values, and seems to be justified by full-scale climb figures.

The variation in fuselage drag with incidence is taken from a model test. The nacelles are treated in a similar manner; N.A.C.A. 415 has proved very useful here, as the results are given for a large number of different positions of the nacelles with respect to the wing, and also for the wing with no nacelles. The effect of interference is thus included.

The complete characteristics are set out in a table as follows:—

C_L	α_0	α_i	α	C_{D0}	Wing C_D	Fuselage ΔC_D	Nacelle ΔC_D	Total ΔC_D	C_B	Total C_D

The table is completed over a range of C_L from zero to the maximum.

The last column but one contains C_B, the body drag, or total drag other than wings; it is equal to the sum of the C_D corresponding to the minimum total (less wings) drag area and the total ΔC_D due to incidence for fuselage and nacelles.

The wing C_D, body C_B and total C_D are conveniently plotted in polar form as shown in Fig. 4. The induced drag coefficient is also given, dotted, on this figure.

Airscrew Characteristics.

The object of the airscrew is to convert the engine torque into forward thrust. Before thrust or thrust horse-power can be calculated, therefore, something must be known about the performance of airscrews.

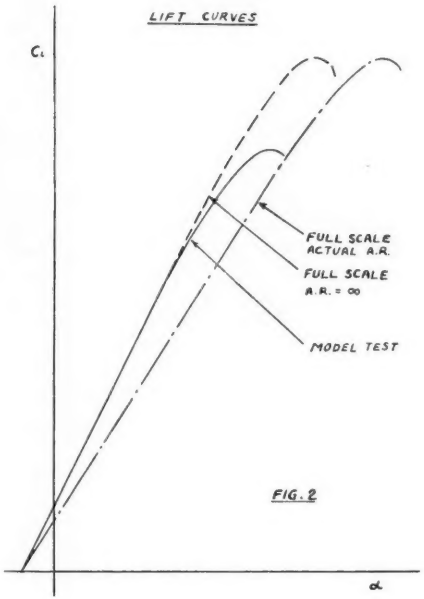

LIFT CURVES
C_L
FULL SCALE ACTUAL A.R.
FULL SCALE A.R. = ∞
MODEL TEST
α

FIG. 2

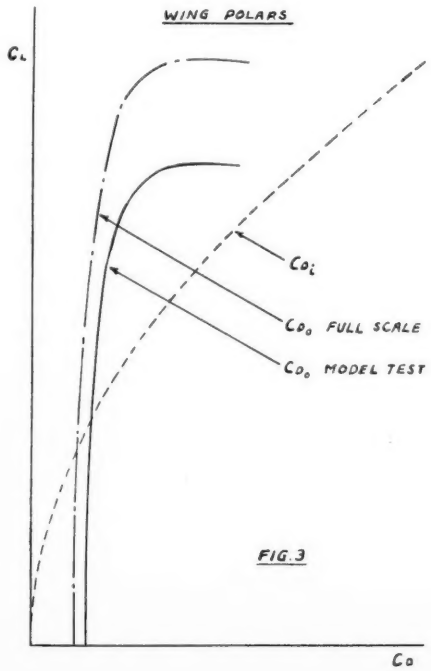

WING POLARS
C_L
C_{D_i}
C_{D_0} FULL SCALE
C_{D_0} MODEL TEST
C_D

FIG. 3

For an airscrew of any given blade shape and number of blades it can be shown that

$$\text{Thrust} = T = \rho n^2 D^4 \phi_1 (V/nD) \quad . \quad . \quad . \quad . \quad (11)$$

$$\text{Torque} = Q = \rho n^2 D^5 \phi_2 (V/nD) \quad . \quad . \quad . \quad . \quad (12)$$

where ρ = mass density.
n = revolutions per second.
D = airscrew diameter.
V = forward speed of aircraft.

V/nD is the advance per revolution; it is written J for short. The functions $\phi_1 (V/nD)$ and $\phi_2 (V/nD)$ are known as "thrust coefficient" and "torque coefficient" respectively, and are denoted by K_T and K_Q, so that we have

$$T = K_T \rho n^2 D^4 \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$Q = K_Q \rho n^2 D^5 \quad . \quad . \quad . \quad . \quad . \quad (14)$$

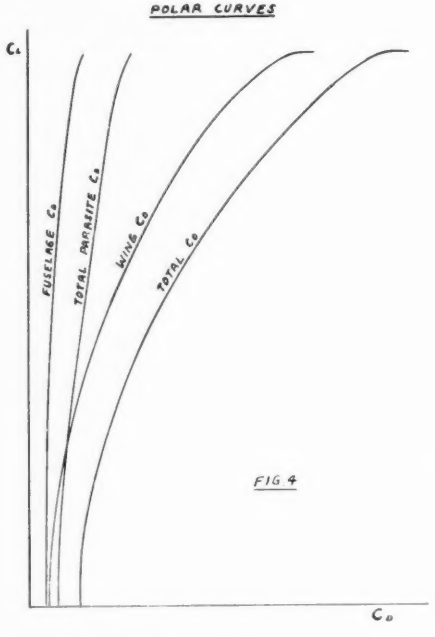


FIG. 4

The variation of K_T and K_Q with J is of the same general type for all airscrews, but the exact nature of this variation is affected to a considerable degree by a number of factors, for example, the ratio geometric pitch/diameter, the ratio maximum blade width/diameter, the thickness ratio of the aerofoil sections used, the plan form of the blades, and, of course, the number of blades.

The usual meaning of pitch with reference to screws of any kind is advance per revolution—V/nD in fact. Since an airscrew does not work in a solid medium, the pitch can be anything according to the instantaneous operating conditions. Some arbitrary definition must therefore be adopted for the pitch at the advance per revolution at which the screw is designed to operate. The one now used is the one generated when the chord line of the blade section at an arbitrary fraction of the tip radius is working at zero incidence, *i.e.*, it is a function of the blade setting or angle between the blade chord line and the polar plane of the airscrew. This is termed "geometric pitch." In this country it is

usually measured at 0.75 tip radius; in America I believe that 0.7 tip radius is sometimes adopted as the standard.

The ratio geometric pitch/diameter, or P/D, is of more interest than the pitch itself. The variation of K_T and K_Q, with J and P/D, is shown in Fig. 5. The full curves refer to an airscrew of low pitch, of a type suitable for an aeroplane having a maximum speed of less than, say, 150 m.p.h., the dotted ones refer to an airscrew of high pitch, such as might be fitted to a machine capable of 200 m.p.h. or more.

It will then be noticed that the latter curves have kinks in them at low values of J; these are due to stalling of the blades brought about by the combination of low forward speed and high blade setting angle.

The effect of variation in number of blades and blade width is what might be expected; and the change in either of these produces a change in the same direction in K_T and K_Q. Doubling the number of the blades, for example, slightly less than doubles the value of the coefficients at a given value of J.

Theoretically a very large number of measurements would have to be made to obtain characteristics for airscrews of all conceivable kinds; fortunately, however, it is possible to make use of a much smaller number and apply corrections for the others without incurring errors of great magnitude. The effect of a change in blade width, for instance, can be allowed for by multiplying the thrust and torque coefficients for a given J by a mean factor which depends only on the ratio blade width/diameter and not on anything else.

For each type of blade, therefore, a family of characteristic curves K_T and $K_Q \sim J$, must be obtained for a range of pitch ratios for various numbers of blades.

A few curves for airscrews of blade widths other than the standard one to which these curves apply are also required to obtain a mean curve for the correction factor mentioned above.

A third important characteristic of an airscrew is the efficiency; this is defined in the usual manner as output/input, that is,

$$\text{Efficiency} = \eta = \frac{\text{work done by thrust}}{\text{torque absorbed}}$$

$$\text{or alternatively } \eta = \frac{\text{thrust h.p. produced}}{\text{torque power absorbed, } i.e., \text{ engine b.h.p.}} \quad . \qquad (15)$$

Now

$$\begin{aligned} \text{Thrust h.p.} &= THP = TV/550 \\ &= K_T \rho n^2 D^4 V/550 \quad . \quad . \quad . \quad . \quad . \qquad (16) \end{aligned}$$

and

$$\begin{aligned} \text{Torque or b.h.p.} &= BHP \\ &= 2\pi n Q/550 \\ &= 2\pi n K_Q \rho n^2 D^5/550. \end{aligned}$$

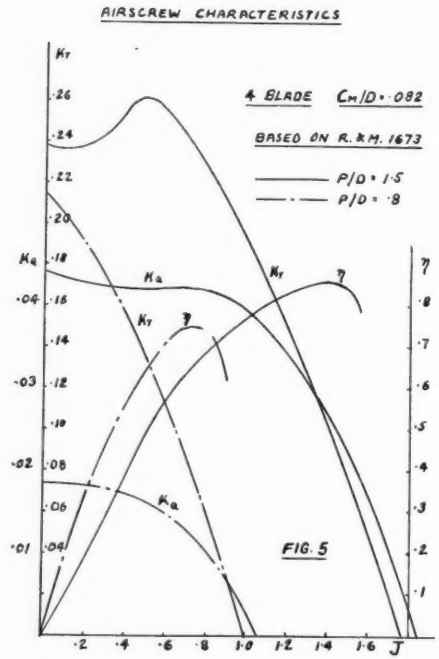
Substitution in equation (15) shows that

$$\begin{aligned} \eta &= (1/2\pi)\ (V/nD)\ (K_T/K_Q) \\ &= (J/2\pi)\ (K_T/K_Q) \quad . \quad . \quad . \quad . \quad . \qquad (17) \end{aligned}$$

The efficiency is calculated from this equation over the range of J, and plotted on the same diagram as the thrust and torque coefficients.

Curves for the two airscrews already mentioned are shown in Fig. 5.

It will be noted that the maximum efficiency occurs at a value of V/nD equal to about 0.7 or 0.8 of that at zero thrust, *i.e.*, K_T and that it improves as the pitch ratio increases; the efficiency value might not be more than 70-75 per cent. for an airscrew designed for a 100 m.p.h. light aeroplane, and might approach 88 per cent. for a 300 m.p.h. fighter, or even 90 per cent. if thin section metal blades are used.

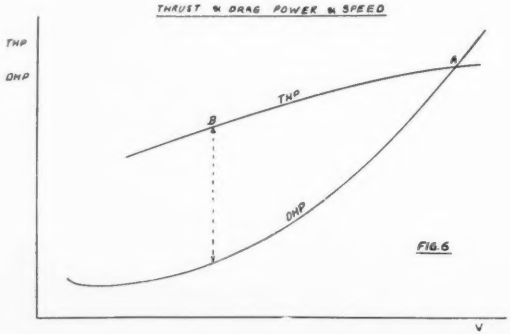


If the tip speed of the blades is more than about 800-900 ft./sec., the efficiency is reduced owing to the higher effective drag. The order of the reduction for the values of the tip speed commonly met with may be 1-2 per cent.

LEVEL SPEED AND CLIMB.

The general method used for the calculation of the maximum level speed and rate of climb characteristics of an aeroplane is the determination, at a number of heights, and over a range of forward speed, of the horse-power required to overcome the drag, and the thrust horse-power available at full throttle.

These, which for the sake of brevity, will be called simply " thrust horse-power " (*THP*) and " drag horse-power " (*DHP*) respectively, are plotted against speed, as shown in Fig. 6.



The point at which the two curves intersect, shown at A, gives the maximum speed; the speed at which the difference between *THP* and *DHP* is greatest, shown at B, is the speed at which the greatest rate of climb will occur. The difference in power is that available for doing work other than overcoming drag, that is, for climb. From consideration of work done in climbing, if

W = total weight of aircraft (lbs.),

V_c = rate of climb (ft./min.),

CHP = horse-power available for climb,

then

$$V_c = 33{,}000\ (CHP/W) \quad . \quad . \quad . \quad . \quad (18)$$

The *THP* and *DHP* curves, therefore, provide all the information required to find the maximum speed and climb performance at any height.

Let us now consider how to obtain these curves.

Take the *DHP* first.

For level flight, the lift must be equal to the total weight, so by equation (4),

$$W = C_L \tfrac{1}{2}\rho V^2 S_w \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Rewriting this

$$\tfrac{1}{2}\rho V^2 S_w = W/C_L$$

and substituting in (5) shows that

$$D = W\ (C_D/C_L).$$

Then

$$DHP = W\ (C_D/C_L)\ (V/550) \quad . \quad . \quad . \quad . \quad (20)$$

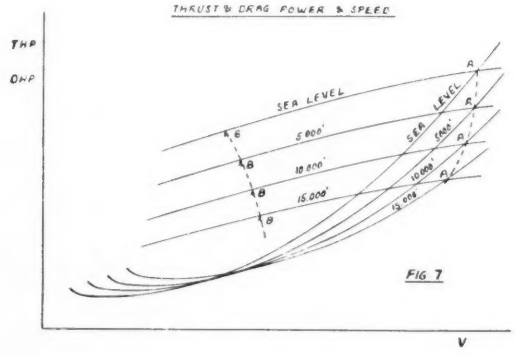


FIG 7

If this process is carried out for a series of values of C_L a curve of $DHP \sim V$ can be plotted from such results.

Suppose now that such a curve has been obtained for sea level density.

To obtain the corresponding curves for various altitudes there is no need to repeat every step for each one. At a given C_L it is apparent from equation (19) that the value of V must be $V_o\sqrt{\sigma}$, where V_o is the corresponding sea level speed and σ the relative density. From equation (20) it then follows that $DHP_o\sqrt{\sigma}$ is the *DHP* at that C_L, where DHP_o is the corresponding sea level *DHP*. That is to say, for any height, the sea level values of *DHP* and V are each divided by the square root of the relative density for that height. A series of heights is thus dealt with quickly, and the resulting curves would be of the type shown in Fig. 7.

It will be noted that the extra drag due to the increased velocity in the slip-stream has not been taken into account. It can be shown that this is the equivalent, for normal flight, of an almost constant percentage of the thrust horse-power,

depending on how much of the aeroplane is affected by the slip velocity. This cannot be considered in detail here, but the practical result is that the effect can be allowed for by multiplying the airscrew efficiency by a factor which for a given aeroplane varies only with airscrew diameter. The latter being also fixed in any particular series of calculations, it follows that if

η_P = net or propulsive efficiency allowing for drag due to slipstream,
η = the free or model efficiency, and
η_{PR} = the factor defined above, termed " propulsive efficiency ratio,"

then

$$\eta_P = \eta \times \eta_{PR} \quad . \quad . \quad . \quad . \quad . \quad (21)$$

The value of η_{PR} is usually between 0.88 and 0.95.

Estimation of the thrust horse-power can now be considered.

For this are required the engine makers' power curves, the airscrew specification, that is, details of number of blades, pitch and blade width ratios, and diameter, and airscrew characteristics appropriate to such specification.

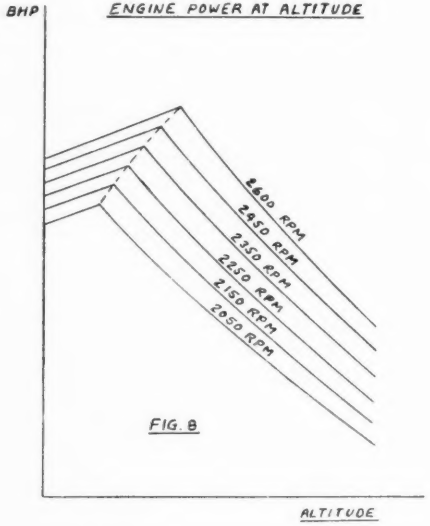


FIG. 8

It has already been seen that

$$BHP = 2\pi n K_Q \rho n^2 D^5 / 550 \quad . \quad . \quad . \quad . \quad . \quad (22)$$

Transposition of this shows that

$$K_Q = (550/2\pi\rho D^5)\,(BHP/n^3)$$
$$= C\,(BHP/n^3) \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where

$$C = (550/2\pi\rho_0 D^5)\,(1/\sigma) = \text{const.}/\sigma \quad . \quad . \quad . \quad (24)$$

Also if

ρ_0 = air density at S.L. = 0.00238 slugs/cu. ft.
N = engine r.p.m.
G = airscrew/engine gear ratio,

then

$$n = NG/60 \quad . \quad . \quad . \quad . \quad . \quad (25)$$

(since n is in revs. per second).

For any value of N, therefore, the BHP is obtained from the engine power curves. As supplied by the engine makers these are plotted as BHP versus height

with r.p.m. as parameter, as shown in Fig. 8. Owing to drawing errors, etc., the variation of BHP with r.p.m. according to these curves is not always smooth, they should therefore be redrawn in the form shown in Fig. 9, *i.e.*, as BHP versus r.p.m. at various heights.

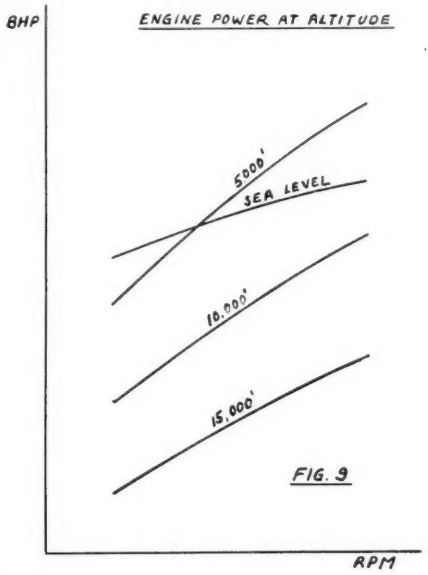
These latter curves are used for the actual work.

Then n and K_Q follow from equations (25) and (23) respectively.

Since K_Q is known, J is found from the airscrew curve. Now, by definition

$$J = V/nD$$

$$V = JnD \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$



Also, η follows from the appropriate airscrew curve, η_P from equation (21), and finally

$$\text{Net } THP = \eta BHP \quad . \quad . \quad . \quad . \quad . \quad (27)$$

(The term net THP is used here to indicate that the drag due to slipstream has been debited, thus distinguishing it from the gross THP, which term is used when such has not been done.)

The calculations of V and net THP are set out for each height in tabular form, being made for about half a dozen values of N, starting at the maximum rated and working downwards in steps of about 100 r.p.m., as follows :—

BHP	N	n	nD	n^3	BHP/n^3	K_Q	J	V	η	η_P	Net THP

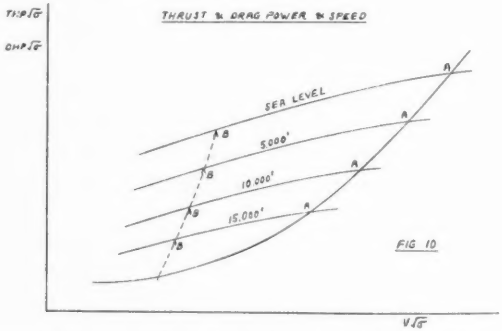
Such a table is completed for various heights, from sea level to somewhere near the ceiling. Curves of $THP \sim V$ (from this point onwards the word net

will be assumed to be understood unless otherwise stated) can then be plotted on the same sheet on which the DHP curves have been drawn. The result might be as shown in Fig. 7 for unsupercharged engines (blown engines will be considered later).

Now it will be remembered that the DHP curves for heights other than sea level were derived from the sea level curve by dividing V_o and DHP_o by $\sqrt{\sigma}$. It is therefore apparent that if $DHP\sqrt{\sigma}$ were plotted against $V\sqrt{\sigma}$ (*i.e.*, against indicated speed) one curve would apply to all heights, and considerable work would be saved.

When this is done the same process must be applied to the THP curves to bring them into line, that is, $THP\sqrt{\sigma}$ must be plotted against $V\sqrt{\sigma}$. The series of curves then appears as in Fig. 10. The points AA show the indicated maximum speeds at the various heights, similarly the points BB corresponding to the greatest intercepts between the two curves show the best indicated climbing speed, and the intercepts themselves are equal to climb $HP\sqrt{\sigma}$. The actual speeds and climb HP are then obtained by dividing these quantities by $\sqrt{\sigma}$.

Enough data is now available to calculate the complete climb and level speed summary; before this calculation is described, however, an alternative system for some of the processes will be given.



It has been seen that the method of plotting $HP\sqrt{\sigma}$ against $V\sqrt{\sigma}$ instead of HPV, has transferred the effect of height entirely to the thrust power curves. A change of weight, however, affects the drag power curve, but not the thrust power ones. The alternative method to be described transfers the effect of change of weight also to the thrust power curves. The resulting drag power curve becomes, in fact, independent of everything except the external shape of the aeroplane. The method is as follows:—

Substituting for D and V in the equation

$$DHP = DV/550$$

shows that

$$DHP = (W/550)\{\sqrt{(2W/\rho S_w)}\}(C_o/\sqrt{C_L^3}) \quad . \quad . \quad (28)$$

and equation (19) may be written

$$V = \{\sqrt{(2W/\rho S_w)}\}(1/\sqrt{C_L}) \quad . \quad . \quad . \quad . \quad (29)$$

Therefore, since S_w is fixed, at any given weight and height,

$$DHP = \text{const.} \times C_D/\sqrt{C_L^3} \quad . \quad . \quad . \quad . \quad (30)$$

$$V = \text{const.} \times 1/\sqrt{C_L} \quad . \quad . \quad . \quad . \quad . \quad (31)$$

In other words, $DHP \propto C_D/\sqrt{C_L^3}$ and $V \propto 1/\sqrt{C_L}$; hence a curve of $C_D/\sqrt{C_L^3}$ plotted against $1/\sqrt{C_L}$ is equivalent to one of DHP against speed which holds for all heights and all weights, since the values are non-dimensional coefficients which are calculated directly from the overall polar curve for the aircraft.

Obviously, the thrust power curves must be converted to absolute coefficients to enable them to be used in conjunction with the curve $C_D/\sqrt{C_L^3} \sim 1/\sqrt{C_L}$, or "characteristic curve," as it is called.

To enable this to be done it is necessary to invent an artificial thrust coefficient which has nothing whatever to do with the relation between the thrust and the physical properties of the airscrew, but is defined in a manner similar to that used for lift and drag coefficients, that is to say, by the equation,

$$\text{Thrust} = C_T \tfrac{1}{2}\rho V^2 S_w \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

This may seem at first to be rather an unreal sort of relationship; a moment's thought, however, shows that it is exactly analogous to the drag equation

$$D = C_D \tfrac{1}{2}\rho V^2 S_w$$

except that it refers to forward thrust instead of backward resistance. For steady level flight, in fact, C_T and C_D are numerically equal.

Now just as in equation (28)

$$DHP = (W/550)\ \{\sqrt{(2W/\rho S_w)}\}\ (C_D/\sqrt{C_L^3})$$

it can be shown that

$$THP = (W/550)\ \{\sqrt{(2W/\rho S_w)}\}\ (C_T/\sqrt{C_L^3}) \quad . \quad . \quad (33)$$

that is to say,

$$THP = \text{const.} \times C_T/\sqrt{C_L^3} \quad . \quad . \quad . \quad . \quad (34)$$

and equation (31)

$$V = \text{const.} \times 1/\sqrt{C_L} \text{ holds as before.}$$

Therefore, $THP \propto C_T/\sqrt{C_L^3}$, and, of course, $V \propto 1/\sqrt{C_L}$ as has been already seen, so that curves of $C_T/\sqrt{C_L^3} \sim 1/\sqrt{C_L}$ are equivalent to ones of $THP \sim V$. These latter have already been obtained; values of $C_T/\sqrt{C_L^3}$ and $1/\sqrt{C_L}$ are found by dividing them by the constants of equations (34) and (31) for the appropriate height. The latter quantities are termed "power coefficient" and "speed coefficient" respectively, and denoted by $\bar{p}$ and $\bar{v}$, so that

$$\bar{v} = \sqrt{(2W/\rho S_w)} \quad . \quad . \quad . \quad . \quad . \quad (35)$$

$$\bar{p} = (W/550)\ \{\sqrt{(2W/\rho S_w)}\} = (W/550)\ \bar{v} \quad . \quad . \quad . \quad (36)$$

In practice these coefficients are calculated before the thrust power for the required heights and for the normal total loaded weight.

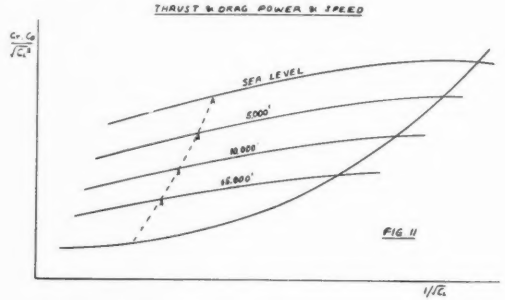
For convenience, the airscrew torque coefficient constant C can be included in the same table, thus:—

Height	σ	$2W/\rho S_w$	$\bar{v}$	$\bar{p}$	C

The calculation of thrust horse-power is carried out as already described, two extra columns being added at the end of the table for $1/\sqrt{C_L}$ and $C_T\sqrt{C_L^3}$, as shown below:—

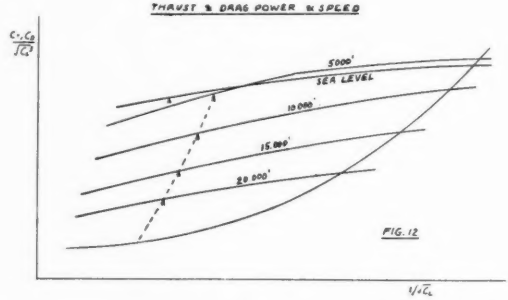
BHP	N	n	nD	n^3	BHP/n^3	K_Q	J	V	η	η_P	Net THP	$1/\sqrt{C_L}$	$C_T/\sqrt{C_L^3}$

There is a point which should be watched when calculating the thrust power of a multi-engined machine. The airscrew characteristics, of course, refer to one airscrew, so that the torque coefficient must be calculated from the BHP of one engine as for a single-engined aircraft. The drag power curve, on the other hand, refers to the whole of the aeroplane, so that the thrust power for all engines must be plotted, not that for one only.



The sheet of thrust and drag power curves are as in Fig. 11, which shows those for unsupercharged engines. It will be noted that the curves are of the same general shape as in Fig. 10, the only difference being found in the denomination of the axes.

With supercharged engines, the BHP at given r.p.m. falls off considerably below the rated height; this has the effect shown in Fig. 12, in which it is seen that the curves for heights below the rated altitude come below that for the rated height itself. The latter, incidentally, has a "shoulder" at the speed corresponding to the r.p.m. at which the particular height is the rated value. (This is different for every r.p.m.; see Fig. 8.)



The performance summary for speed and climb is determined from the thrust-and-drag-power curves as follows. Although the curves are actually of non-dimensional coefficients, the points of intersection still represent the maximum level speed, and the maximum intercept between thrust and drag power, and its position still give the climb HP and best climbing speed. The values of $1/\sqrt{C_L}$ are converted to speeds by multiplying by the appropriate speed coefficients, and the climb HP found by consideration of equations (33) and (28) from which

$$CHP = THP - DHP = \overline{p}\,(C_T - C_D)/\sqrt{C_L}^3 \quad . \quad . \quad . \quad (37)$$

Put into words, the CHP is the product of the intercept just mentioned and the power coefficient for the height concerned. The rate of climb follows from equation (18).

Further, the climbing and maximum speed r.p.m. for each height can be read off a curve of $V \sim$ r.p.m., the relation between them having already been determined in the course of calculating the thrust power (columns 2 and 8 in the appropriate table), see Fig. 13.

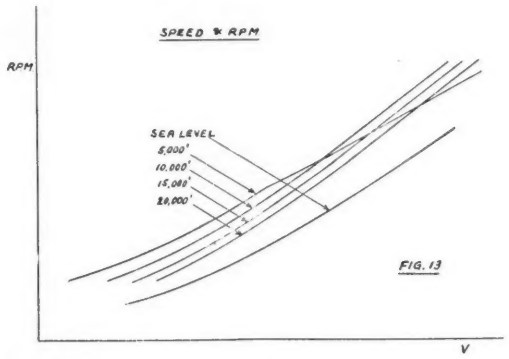


FIG. 13

The summary is set out in tabular form as shown below:—

Height	$\overline{v}$	$\overline{p}$	CLIMB.							LEVEL.			
			$1/\sqrt{C_L}$	V f./s.	V m.p h.	N	$\frac{(C_T - C_D)}{\sqrt{C_L^3}}$	CHP	V_c	$1/\sqrt{C_L}$	V f./s.	V m.p.h.	N

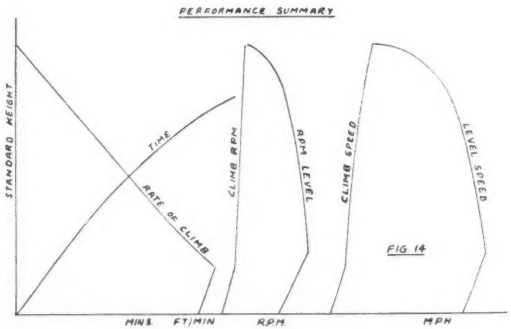


FIG. 14

The rate of climb, climbing speed and r.p.m., and maximum speed and corresponding r.p.m. are plotted against height, as shown in Fig. 14 for an aeroplane with supercharged engines.

Finally, the time required to climb to various heights is calculated and the values plotted on the same sheet.

The mathematical definition of rate of climb is given by

$$V_c = dh/dt \quad . \quad . \quad . \quad . \quad . \quad (38)$$

Integrating this, we have

$$t = \int_{h_1}^{h_2} (1/V_c)\, dh \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

where t = time required to climb from height h_1 to height h_2.

The integration can be carried out very simply by plotting $1/V_c$ against height and finding the area under the curve between limits of sea level ($h = 0$) and various heights. These areas represent the time to height directly in minutes. A curve of this against height is included on Fig. 14.

This completes the maximum speed and climb calculations.

RANGE CALCULATIONS.

The reduction in weight which occurs as an aeroplane uses up fuel has a considerable effect on the power required to fly it at a given speed. This effect must be allowed for in calculating the range obtainable with a given fuel load or the quantity of fuel required for a given range.

The condition of flight for cruising that will be considered here is that the engine(s) is throttled for level flight at normal r.p.m. Still air will be assumed.

The cruising speeds for various weights are first obtained by the following method.

It is known that the engine BHP is less than the full throttle value for the particular height and r.p.m., but it is not known what the actual value is. A series of values is therefore taken, starting at the full throttle value and working downwards in steps of about 10 per cent. of it.

From equation (23) $K_Q = \text{const.}\ (BHP/n^3)$ at any given height.

For cruising at constant r.p.m., n is also fixed. Hence, we have

$$K_Q = \text{const.} \times BHP \quad . \quad . \quad . \quad . \quad . \quad (40)$$

From K_Q follow J, V, η, $\eta\rho$ and net THP exactly as for a full throttle calculation, except that as BHP decreases, K_Q decreases instead of increases; hence J and V increase.

$1/\sqrt{C_L}$ and $C_T/\sqrt{C_L}^3$ are also obtained as before, *i.e.*, by dividing V and THP by the speed and power coefficients respectively which correspond to a series of weights from the minimum possible for the loaded aircraft (less fuel) up to the maximum overload value or a bit more.

The table is shown below, thus:—

BHP	K_Q	J	η	η_P	V	THP	$W = W_1$		$W = W_2$	
							$1/\sqrt{C_L}$	$C_T/\sqrt{C_L}^3$	$1/\sqrt{C_L}$	$C_T/\sqrt{C_L}^3$

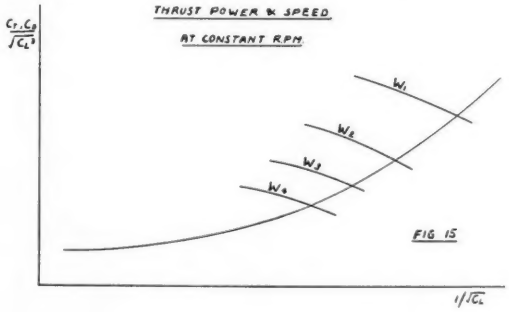
A total of about four or five weights is considered. The curves are plotted out on a sheet on which is also drawn the characteristic curve, as shown in Fig. 15. The intersections represent the cruising speeds for the various weights, also the net THP, equal to the drag power, or $p \times C_D/\sqrt{C_L}^3$.

From V follows J (since nD is constant with the r.p.m. and therefore known) and then η from the airscrew curve.

Hence η_P from equation (21) and BHP from equation (27).

The specific fuel consumption, that is, the consumption per unit power per unit time, usually expressed as pints/BHP/hour varies both with BHP and r.p.m. For cruising at high speeds, however, the variation with BHP is small, and it is usually considered sufficiently accurate to use a mean value selected from curves supplied by the engine makers.

For a normal type of engine supercharged to 10,000 feet or so the value might be about 0.55 pints/BHP/hour.



If the specific consumption be denoted by K, and the weight of the fuel be P pounds per gallon, then the distance flown in miles per pound of fuel consumed, say R, is given by

$$R = 8V\ (\text{m.p.h.})/(K,\ P,\ BHP) = \text{const.}\ (V/BHP) \quad . \quad . \quad (41)$$

The calculation of R for various weights is tabulated as follows:—

Weight.	$1/\sqrt{C_L}$	$\overline{v}$	V f./s.	V m.p.h.	J	η	η_P	$C_D/\sqrt{C_L^3}$	$\overline{p}$	Net THP	BHP	R

Now the change in weight of the aircraft in any given time equals the weight of fuel consumed, hence if s be a measure of distance

$$ds/dW = R$$

or integrating

$$s = \int_{W_1}^{W_2} R\,dW \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

Therefore, the area under a curve, between any pair of ordinates of $R \sim W$ represents the distance flown in consuming a quantity of fuel equal to the difference between the weights for those ordinates, and successive integration of such a curve with a lower limit equal to the smallest chosen weight and a series of upper limits gradually increasing until the highest chosen value is reached, gives a series of values of s.

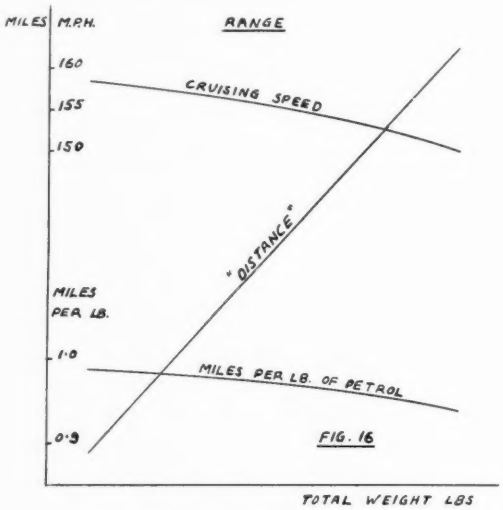
If these are plotted against W, a curve is produced from which can be read the fuel required for a given range, or the range available with given fuel, by the following means:—

If W_A be the weight of the aircraft less all petrol, but including, as a first approximation, a guess allowance for oil and W_B the weight with fuel, but

excluding that for take-off and climb to operating height, then the difference between the distance values corresponding to these two weights is the range for a weight of petrol equal to $W_B - W_A$.

For convenience in calculation the oil is assumed to be carried throughout the flight; this introduces a slight error on the conservative side, since at a given speed, slightly less power would be required at the lower mean weight.

The speed in m.p.h. is also plotted against W, and the order of variation in this and R are indicated in Fig. 16.



The speed corresponding to the mean of W_A and W_B is the mean speed for the flight. Besides being of interest in itself, it is used to determine the actual quantity of oil required.

Range divided by mean speed is the endurance or time of flight; the product of this and the cruising oil consumption figure, supplied either by the engine makers or the Air Ministry, and usually quoted in pints/hour, is the quantity of oil which standard engines in good condition should use for the flight. A suitable excess is added to allow for engines, which, owing to wear or some other factor, may have a consumption higher than standard. An additional allowance is made for take-off and climb to operating height.

Now that the true weight of oil is known, W_A and W_B are corrected for the error in the original guess; the small change of weight due to this correction only causes errors too small to notice in the values of range, fuel required, or mean speed.

The tabulation is as shown below for a series of loads or ranges:—

Range.	Load.	W_A	W_B	Petrol for Range.		Total Petrol. gals.	Mean Weight.	Mean Speed. m.p.h.	Endurance. hours.	Oil for Range. gals.	Total Oil. gals.
				lbs. $= W_B - W_A$	gals.						

The total fuel is found by adding to the fuel for range, that is $W_B - W_A$ lbs. or $(W_B - W_A)/P$ gallons, a suitable allowance for take-off and climb to operating height. The weight of this added to W_B gives the total take-off weight.

The table shown above can be used either when calculating the fuel for given ranges or ranges for given fuel loads. In the former case the columns are filled in, in the order in which they are given; in the latter, a different order would be adopted, columns 2 to 7 being filled in first, then column 1, and then the others as before.

TAKE-OFF RUN.

The estimation of the length of the horizontal run required to take-off over a barrier resolves itself into the calculation of the thrust and drag as functions of forward speed, and suitable integration of the accelerating force, equal to the difference between them. It should be noted that the actual forces are required, rather than the corresponding powers.

Consideration will first be given to the thrust curve. The method used is to some extent similar to that for calculating the *THP* for level speed and climb which has already been described.

Starting with the values of *BHP* and r.p.m., K_Q is found as before by equation (23), and J and η (the gross or "free air" value) are obtained from the airscrew curves. It will be remembered that the net or propulsive efficiency was assumed to be a constant fraction of the model value for normal flight. At low speeds, however, this assumption does not hold; the actual variation must be taken into account.

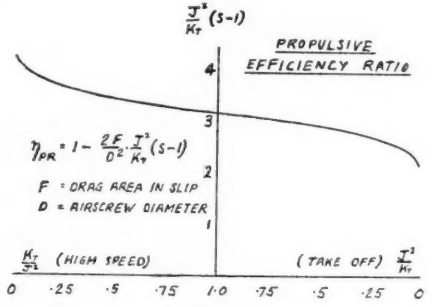


FIG. 17

It can be shown (1) that the propulsive efficiency ratio is given by

$$\eta_{PR} = 1 - (2F_s/D^2)\,(J^2/K_T)\,(S-1) \quad . \quad . \quad . \quad (43)$$

where F_s = drag area of parts within the slipstream.

D = airscrew diameter.

S = slip factor.

The slip factor is defined as the square of the ratio of the mean velocity in the slipstream to the forward speed of the aircraft. This is a function of thrust coefficient, based on the assumption that if such mean slipstream speed were the actual speed in a tube concentric with the thrust axis of outside diameter 0.8 D and inside diameter 0.2 D, and that the speed outside those limits were the forward speed, the gross thrust would be the same as it actually is. The final equation is

$$\sqrt{S} = \tfrac{1}{2}\,(1 + \sqrt{[1 + 8.48\,K_T/J^2]}) \quad . \quad . \quad . \quad (44)$$

Since S depends only on K_T and J standard curves of $S \sim K_T/J^2$ can be drawn. Further, the expression $(J^2/K_T)\,(S-1)$ similarly contains only the same variables, and a standard curve can be drawn against K_T/J^2 and J^2/K_T. This is given in Fig. 17. It will be noticed that both these latter coefficients are used as abscissæ

for the same curve. The reason for this is that as J approaches zero, K_T/J^2 tends to become infinite; by working with the reciprocal for all values greater than unity, the numbers become such that a single curve covers the whole range.

For any value of r.p.m., J is found as described. K_T follows from the airscrew characteristics, K_T/J^2 or J^2/K_T by calculation, and $(J^2/K_T)(S-1)$ from the curve just referred to.

F_s and D are known, so that η_{PR} can be obtained from equation (43).

Now the torque is given by

$$Q = 550\ BHP/2\pi n \quad . \quad . \quad . \quad . \quad . \quad (45)$$

and the net thrust by

$$\text{Net } T = \eta_{PR} \text{ gross } T$$
$$= \eta_{PR} K_T \rho n^2 D^4 \quad . \quad . \quad . \quad . \quad . \quad (46)$$

also, repeating equation (14),

$$Q = K_Q \rho n^2 D^5$$
$$\therefore \text{ Net } T/Q = \eta_{PR} K_T \rho n^2 D^4 / K_Q \rho n^2 D^5$$

or

$$\text{Net } T = (Q/D)\, \eta_{PR}\, (K_T/K_Q) \quad . \quad . \quad . \quad . \quad (47)$$

The tabulation is as follows:—

BHP	N	n	nD	n^3	BHP/n^3	K_Q	J	K_T	K_T/J^2	$\frac{(J^2/K_T)}{(S-1)}$	η_{PR}	BHP/n	Q	$\frac{K_T}{K_Q}$	Net T	V	V^2

The column for V^2 is included for a reason, which will be given later. The table should be completed for five or six values of V^2 between zero and about $(1.5\ V_s)^2$ where V_s is the stalling speed. The result is plotted as a curve of net thrust against V^2.

Consider now the effects of the slipstream on lift and drag. The following method of calculation has been evolved by R. S. Stafford.

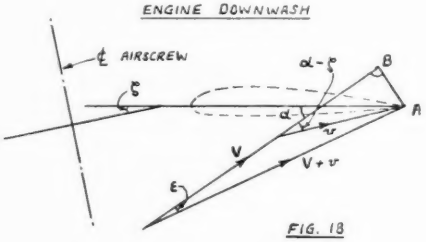


FIG. 18

It is assumed that the effect on lift can be divided into two separate parts—an increase due to the higher velocity and a reduction due to engine downwash.

The slipstream boundaries are assumed to be the same as those already given in connection with the propulsive efficiency ratio. Considering increased velocity only, if S'_w be wing area affected, the lift increase due to slip velocity is given by

$$\Delta L_1 = C_{L\frac{1}{2}} \rho S'_w V^2 (S-1)$$
$$= \text{const. } C_L V^2 (S-1) \quad . \quad . \quad . \quad . \quad (48)$$

Taking next the reduction due to engine downwash, the latter is first found by consideration of the resultant velocity.

In Fig. 18 is shown a wing operating at speed V and incidence α. The increase in velocity is parallel to the thrust axis, set at ζ to the wing, and therefore inclined to V at $\alpha-\zeta$. The engine downwash, or reduction in effective incidence, denoted by ϵ, is the angle between the forward speed and the resultant velocity, which is equal to $V\cos\epsilon+v\cos(\alpha-\zeta-\epsilon)$; since the angles concerned are all small, this may be written $V+v$ without incurring serious error.

If AB be perpendicular to the line of direction of V, then

$$(V+v)\sin\epsilon=AB=v\sin(\alpha-\zeta) \quad . \quad . \quad . \quad (49)$$

or since ϵ and $\alpha-\zeta$ are small

$$\epsilon=\{\,v/(V+v)\,\}(\alpha-\zeta) \quad . \quad . \quad . \quad . \quad (50)$$

$v/(V+v)$ is a function only of S; it can therefore be drawn as a standard curve, reproduced in Fig. 19.

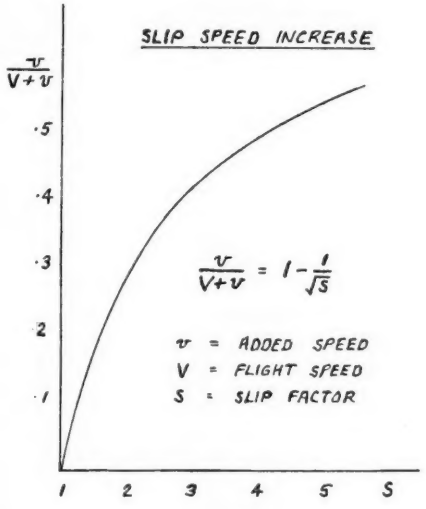


FIG. 19

As has been said, ϵ is the reduction in incidence due to slipstream; then if $\partial C_L/\partial\alpha$ be the slope of the lift curve the change in effective C_L is

$$\Delta C_L=-\epsilon\partial C_L/\partial\alpha \quad . \quad . \quad . \quad . \quad . \quad (51)$$

Hence, with the same notation as before, change in lift due to engine downwash is given by

$$\begin{aligned}\Delta L_2&=\Delta C_L\tfrac{1}{2}\rho V_s^2S'_w\\&=-\epsilon\,(dC_L/d\alpha)\,\tfrac{1}{2}\rho V_s^2S'_w\\&=\text{const. }\epsilon V_s^2 \quad . \quad . \quad . \quad . \quad . \quad (52)\end{aligned}$$

then

$$\text{net }\Delta L=\Delta L_1+\Delta L_2 \quad . \quad . \quad . \quad . \quad . \quad (53)$$

and

$$\text{Total lift (at } V^2)=W+\text{net }\Delta L \quad . \quad . \quad . \quad (54)$$

The value of V^2 used throughout the above is that for level flight. Therefore the aeroplane will climb, since the lift is greater than the weight, at the level flight, C_L corresponding to this V^2. In other words, the effective lift coefficient is increased in the ratio total lift/weight, so that to retain level flight, the speed squared must be reduced in the inverse of this ratio, *i.e.*,

$$\text{Corrected } V^2=\text{level flight } V^2\,(W/\text{total lift}) \quad . \quad . \quad . \quad (55)$$

Now the increase in drag due to slipstream has already been allowed for by means of a reduction in thrust; hence the engine-off value of L/D, appropriate to a given C_L, may be assumed to hold, and the (net) drag is given by

$$\text{Drag} = W/(L/D) \quad . \quad . \quad . \quad . \quad . \quad (56)$$

This drag and corrected V^2 are calculated over a range of values of C_L from the maximum down to about half that value. They are plotted on the same sheet as the thrust and represent the airborne drag during the initial climb.

The table takes the form :—

C_L	V^2	S	$v/(V+v)$	a	$a-\zeta$	ϵ	$V^2(S-1)$	V_g^2	ΔL_1	ΔL_2	Net ΔL	Total lift at V^2	Corresponding V^2	L/D	Drag.

The calculation is done for one or more total weights; a curve of $S \sim V^2$, which applies for all weights, is obtained beforehand in a separate table.

It is admitted that the theory of the method just described contains a number of approximations—obviously, for example, there are no definite boundaries to the slipstream—but analysis of wind tunnel tests with airscrews running has shown that the agreement for lift is almost exact and that for drag the errors are quite small.

Considering now the drag during the unstick run itself, the aircraft is assumed to be at a constant attitude, the fuselage being horizontal. In other words, the C_L is taken as being constant.

This being so, the lift is directly proportional to V^2, and since the total weight is constant, the ground friction is also directly proportional to V^2. Further, so is the air drag, so that the total resistance to motion, ground friction plus air drag, has a straight line variation with V^2.

Two points only, therefore, need be calculated. The most convenient ones are those at which each of the respective factors is zero. First, at zero speed, there is no air drag, and all the weight is taken by the ground; the resistance is therefore μW, where μ is the coefficient of friction. Suitable values given by Diehl in N.A.C.A. 450 are as follows :—

Surface.	μ.
Smooth deck, or hard surface ...	0.02
Good field, hard turf	0.04
Average field, short grass	0.05
Average field, long grass	0.10
Soft ground, gravel or sand ...	0.1 to 0.3

Secondly, the ground friction vanishes when the whole weight is airborne; this is a convenient condition to take for the second point.

Since the wing is close to the ground, the vortex image of the circulation provides a considerable reduction in induced downwash and drag, or increases the apparent aspect ratio. This is given by

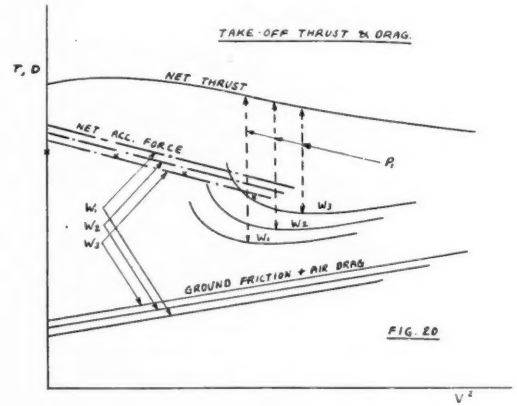
$$AR' = AR/(1-\sigma) \quad . \quad . \quad . \quad . \quad . \quad (57)$$

where AR' = effective aspect ratio, wheels on ground.
AR = actual aspect ratio (span^2/area).
σ = biplane interference factor and is a function of the gap/span ratio, the gap here being the distance between the wing and the vortex image, or twice the height of the wing above the ground.

The lower part of the $C_L \sim \alpha$ curve is recalculated, using the α_i for AR' (see equations (8) and (9)). From the corrected curve is read the value of C_L at the incidence occurring when the fuselage is horizontal.

V^2 and drag with slipstream on are then calculated for this value by the method already given. The value of L/D used in finding the drag is based on the induced drag for the higher aspect ratio.

A straight line through the two points just found, for zero speed and airborne speed, gives the total resistance during the ground run.



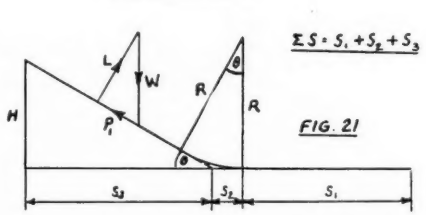
Curves of thrust and drag during the take-off are shown in Fig. 20 for three weights. These curves provide the data required for calculating the take-off run. It may be observed here that in the case of aircraft fitted with slots, the latter will in general be closed during the ground run and open during the initial climb; the values of L/D should allow for this.

The take-off run is considered in three parts:—

1. The ground or unstick run, denoted by S_1.
2. The "get-off," in which the aeroplane is assumed to travel in a circular path at maximum C_L, and which is denoted by S_2.
3. The initial climb over a barrier, the horizontal projection of which is denoted by S_3.

Then the total take-off run over the barrier (see Fig. 21) is given by

$$\Sigma S = S_1 + S_2 + S_3 \quad . \quad . \quad . \quad . \quad . \quad (58)$$



S_2 and S_3 are assumed to occur at any speed V greater than the engine on stalling speed. The speed for minimum total run is usually 8-12 per cent. greater than the engine on stalling speed.

For the unstick run, values of net accelerating force, equal to net $T-D$ are marked on the sheet of curves (Fig. 20). These lie approximately on a straight line, the equation of which is

$$P=a-bV^2 \quad . \quad . \quad . \quad . \quad . \quad (59)$$

where P = net accelerating force, a and b are constants.

It can be shown that

$$S_1=(1.15\ W/gb)\log_{10}\{(a/b)/(a/b-V^2)\} \quad . \quad . \quad (60)$$

S_3 is given by a simple triangle of forces shown on Fig. 21, from which it is evident that, if θ be the climbing angle and H the barrier height

$$S_3=H\cot\theta=H\ \text{lift}/P_1$$

where P_1 = net accelerating force of the airborne aeroplane at speed (see Fig. 20).

Then taking the weight as being equal to the lift, we have

$$S_3=HW/P_1 \quad . \quad . \quad . \quad . \quad . \quad (61)$$

The " get-off " run S_2 is assumed to occur at the same speed as for S_3, and the pilot is assumed to put the aircraft into the attitude for maximum lift, the excess lift overcoming the centripetal force.

It can be shown that the radius of curvature of the arc is given by

$$R=V^2/g\ (C_L\ \text{max.}/C_L-1) \quad . \quad . \quad . \quad . \quad (62)$$

and hence that

$$S_2=(P_1V^2/2gW)\ [1/(V^2/V_0{}^2-1)] \quad . \quad . \quad . \quad (63)$$

where V_0 is the engine in stalling speed.

S_1, S_2 and S_3 can be calculated for various weights, and a curve of total run plotted against weight, either for take-off at a given excess percentage above the stalling speed, or at the optimum speed for each weight, obtained by plotting ΣS against V.

From this curve can be read either the run required for a given total weight or the maximum weight at which the barrier can be cleared with a given run.

In conclusion, I would like to express my thanks to Mr. Stafford for a series of helpful suggestions.

Reference.

1. " The Propulsive Efficiency of an Airscrew." R. S. Stafford, " Flight," 30/3/33.

CRITICAL SPEEDS OF MONOPLANES.

By J. Hanson, B.Sc., D.I.C. (*Student*).

(*Read before the Students' Section of the Society on January 19th*, 1937.)

§1. Introduction.

The fact that attention must be given to stiffness as well as strength in aeroplane design is now generally recognised. The provision of adequate strength alone is not sufficient to ensure that an aeroplane is immune from such troubles as flutter, loss of lateral control due to twisting of the wing and wing divergence. This is illustrated by the case of the Puss Moth. As shown in R. and M. 1645 this machine was examined in detail by the Aeronautical Research Committee and found to be completely satisfactory as far as the existing official airworthiness requirements were concerned, and yet it experienced failures which were attributed to flutter, an instability involving the stiffness of the wings and tail.

In the earlier stages of the investigations into these stiffness problems it appeared to many practical people that the work was of academic interest only. As a matter of fact it was of subsidiary importance while operational speeds of aeroplanes were relatively low, but the higher speeds of the modern aeroplane make such problems of direct practical interest.

The problem of loss of lateral control at high speeds due to twisting of the wing has now reached a reasonably conclusive position and I shall devote most of my attention to this and give, as far as possible, the present position as regards divergence and flutter.

Before considering these problems I propose to deal with two important relevant points :—

(1) The definition and measurement of wing stiffness.
(2) The useful device known as the " semi-rigid wing."

§2. Wing Stiffness.

The stiffness of an aeroplane wing is defined by the values of its flexural and torsional stiffnesses at certain sections along the span. Normally two are taken :—

(1) Mid-aileron ;
(2) Equivalent tip ;

which are indicated in Fig. 1 and defined as follows :—

The mid-aileron section, M.A., is that wing section parallel to the centre line of the aeroplane and midway between the sections containing the ends of the aileron.

In order to avoid difficulties due to local deformation the stiffness is not measured at the actual wing tip, but at the equivalent tip, E.T., which is that section parallel to the centre line which is 0.9 of the semi-span from that centre line.

§2.1. Flexural Centre of a Wing Section.

Considering an aeroplane wing held at the root as in Fig. 2 (the wing root in reference to stiffness being taken as the root in the aerodynamic sense, *i.e.*, at the side of the fuselage in the case of an ordinary monoplane as indicated by W.R. in Fig. 1).

It is obvious that a single normal load applied at random at any section produces twisting of the section as well as normal displacement, as shown in Fig. 2, where

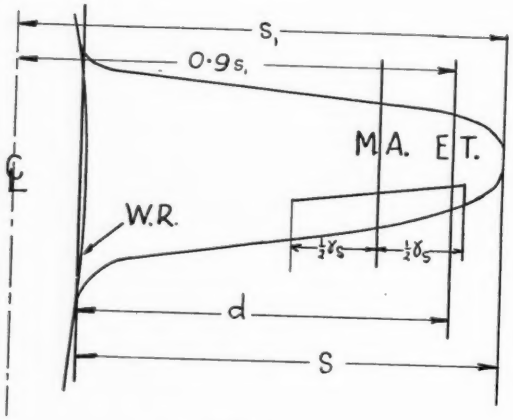


FIG. 1.
Mid-aileron and equivalent tip sections.

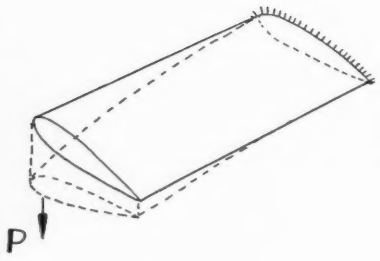


FIG. 2.

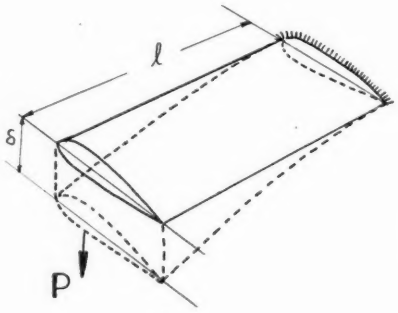


FIG 3.

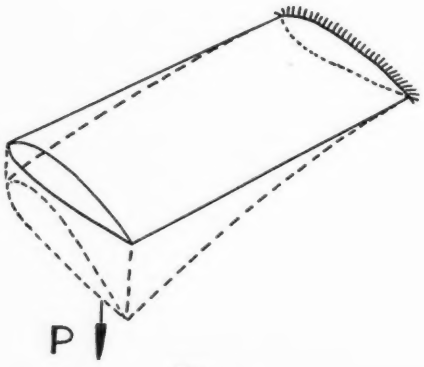


FIG. 4.
Flexural centre of a wing section.

the load is applied near the leading edge of the wing. If the load is applied near the trailing edge, as in Fig. 4, the wing torsion accompanying the lateral bending is of the opposite sign and thus there must be an intermediate point in the section for which, on the application of a normal concentrated load, the section would deflect parallel to itself without twisting, as shown in Fig. 3. This point is called the flexural centre or elastic centrum of that section. Other terms such as principal flexure point and centre of flexure are used with the same significance.

A reciprocal property of the flexural centre is that such a point in a wing section would suffer no lateral deflection under the application of a pure twisting couple applied in that section.

The flexural centre at any section of a wing can be found by experiment on lines suggested in Figs. 2, 3 and 4, this being the usual procedure in the standard stiffness tests of monoplane wings (R. and M. 1742), or calculated by the method of R. and M. 1751, which shows that a reasonable approximation to the flexural centre of a wing section can be obtained by finding the "centre of inertia," *i.e.*, the centre of gravity of the moments of inertia of the separate parts of the section.

For different types of wing construction the variation of the chordwise location of the flexural centre is not very large, as indicated in R. and M. 1596, where an analysis of the stiffness characteristics of a number of cantilever monoplanes shows that the position of the flexural centre varies normally between 0.27 and 0.38 of the chord, only being outside these limits for one or two aeroplanes.

§2.2. Flexural Stiffness.

The flexural stiffness of a wing at any given section is obtained by applying a normal concentrated load at the flexural centre of the section and measuring the resultant purely flexural displacement which occurs at that section. If the section is at a distance l ft. from the wing root (see Fig. 3) and the deflection is δ ft. for a load of P lb., then the flexural stiffness might be defined as P/δ lbs. per ft.; it is convenient, however, to express the stiffness as a moment per radian displacement, thus, since the moment of the load about the wing root is Pl and the deflection at the section expressed in radians is δ/l, the flexural stiffness l_φ is given by

$$l_\varphi = Pl/(\delta/l) = Pl^2/\delta \text{ lbs. ft. per radian} \quad . \quad . \quad . \quad (1)$$

§2.3. Torsional Stiffness.

The torsional stiffness of a wing at any given section is obtained by applying a pure twisting couple in the plane of the section and measuring the resultant purely torsional displacement which will occur at that section. If the couple is T lb. ft. and the twist of the section θ radians relative to the wing root section, then the torsional stiffness m_θ, expressed as a moment per radian displacement is given by

$$m_\theta = T/\theta \text{ lb. ft. per radian} \quad . \quad . \quad . \quad . \quad (2)$$

In this way four stiffness figures, namely, the flexural and torsional stiffnesses at the two sections of the wing, mid-aileron and equivalent tip, are obtained and these provide a simple but effective way of specifying wing stiffness both as regards magnitude and spanwise distribution.

§3. The "Semi-Rigid" Wing.

§3.1. Reason for Use.

In the determination of the various critical speeds of a monoplane involving the stiffnesses of the wings there is one common difficulty. It arises from the fact that the shape of the deflection curve of the wing (torsional or flexural) is dependent upon the distribution of the aerodynamic loads, and therefore upon the speed of the machine. If the structure of the wing is known and its stiffness characteristics have been calculated or measured, its modes of deformation under aerodynamic load can be ascertained in terms of the speed, and it is then possible

to obtain exact solutions to some of the problems, but the procedure is extremely laborious and unsatisfactory for routine work. Even with this information other problems are still intractable and so approximate methods must be used. The approximation used to overcome this difficulty associated with the interdependence of the aerodynamic and elastic actions on the wing is to substitute for the real elastic wing what is called a " semi-rigid " wing.

§3.2. Properties of a " Semi-Rigid " Wing.

Such a wing represents only the more important of the wing deformations and is made elastically similar to the real wing by giving it the same stiffness at some chosen reference section. It also has the very important property that its spanwise curve of deflections follow definite laws independent of variations of loading and speed.

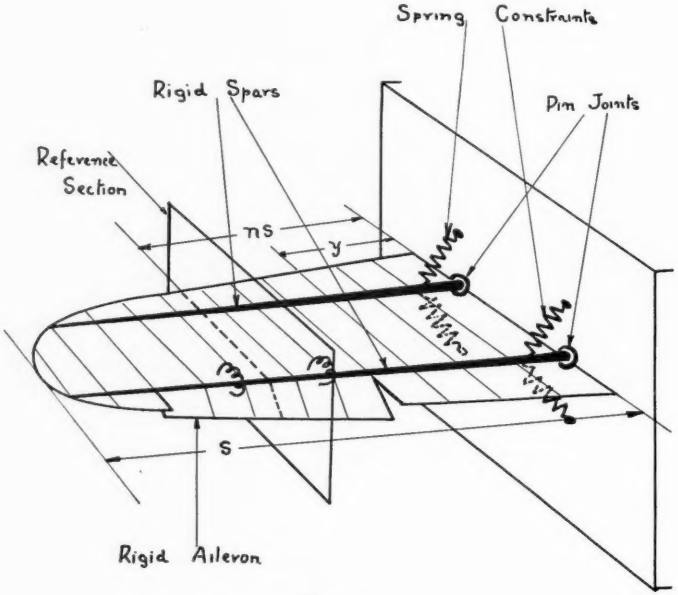


Fig. 5.

Simple semi-rigid wing.

The simplest form of semi-rigid wing is that in which the deflection curve is linear. It could be represented as in Fig. 5 by a wing with infinitely stiff spars pin-jointed at their roots to a rigid wall and controlled there by spring constraints. In such a wing the displacements at any section of the span are always a definite fraction of the displacements at the reference section. Loads applied at any point of the wing can be transferred to the reference section and the whole loading system on the real wing can be represented by equivalent loading actions at the reference section of the semi-rigid wing. Referring to Fig. 5, if the distances from the wing root to the wing tip and to the reference section are respectively s and ns, it is obvious that a load W applied at any section y can be replaced by

$$W \times (y/ns)$$

at the reference section.

The spring constraints are of such stiffnesses as to make the wing stiffness as measured at the reference section equal to that of the real elastic wing at that

section. The rest of the wing structure does not contribute to the elastic properties of the wing, but exists solely for the purpose of transmitting the externally applied loads to the spars and fixing their chordwise position.

The aileron is a rigid body (an assumption justified in practice by setting a sufficiently high minimum limit to its stiffness) connected to the wing in such a way as not to prevent distortion of the latter. It is subject to spring constraint at the hinge line which represents the elasticity of the control circuit and its angle relative to the wing is assumed constant along the aileron span.

As already stated, Fig. 5 illustrates the simplest form of " semi-rigid wing "; laws of spanwise deformation other than linear can obviously be used, of an order appropriate to the deformation to be expected in the problem under consideration. The " linear semi-rigid wing " permits of a simple diagrammatic presentation and thus has been used to explain the device.

§3.3. Success of a Semi-Rigid Wing.

The ability of a semi-rigid wing to represent successfully the real elastic wing depends upon the choices of the representative shape of deformation and the reference section at which the characteristic stiffnesses of the real and semi-rigid wings are made equal.

One guide to the choice of the reference section is given by taking semi-rigid wings with reasonably representative deformation shapes and obtaining the results for the critical speed under consideration for two or three choices of reference section and comparing these results with the values of the critical speed obtained by direct experiment or by exact calculation; this has been done in the case of critical reversal speed.

In more recent unpublished work the guide to the choice of the reference section is given on a systematic basis which, when applied to the problem of reversal of aileron control due to wing twist, gives results in excellent agreement with the former method.

The idea of employing an approximate shape to assist in the solution of an otherwise laborious or intractable problem, is not, of course, entirely novel, being embodied in Rayleigh's Energy Method for determining vibration frequencies and critical loads, and in approximate strength calculations for suspension bridges.

§4. Presentation.

In considering the various critical speeds of a given monoplane, I propose, as far as possible, to deal with each under the following headings:—

(1) Nature of problem.
(2) Analytical solutions, accurate and approximate.
(3) Experimental determination.
(4) Factors influencing the problem.

§5. Critical Reversal Speed.

§5.1. Nature.

When an aeroplane is in stable symmetrical flight the aerodynamic loads on the wings distort them until a position of equilibrium is reached between the external aerodynamic loading actions and the internal elastic restoring actions. If now one of the ailerons is moved down, the direct result is to increase the lift and the rolling moment on that wing. But a " down " aileron also produces a twisting moment on the wing tending to raise the trailing edge of the wing and depress the leading edge, decreasing the incidence and thus neutralising some of the additional lift and rolling moment produced directly by the aileron. The opposite " up " aileron tends to produce increasing incidence, and therefore, lift and rolling moment opposite to its direct effect. Thus, due to the torsional elasticity of the wings, there is a reduction of rolling moment, corresponding to a

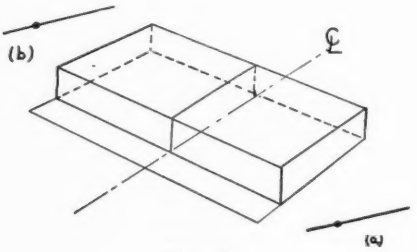


FIG. 6.

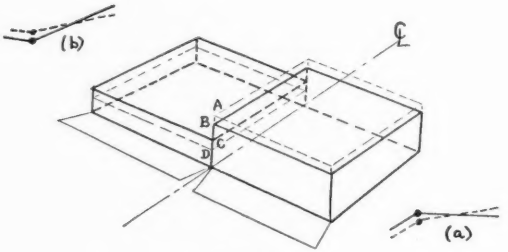


FIG. 7.
$V < V_r$.

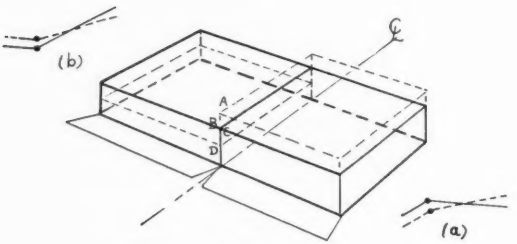


FIG. 8.
$V = V_r$.

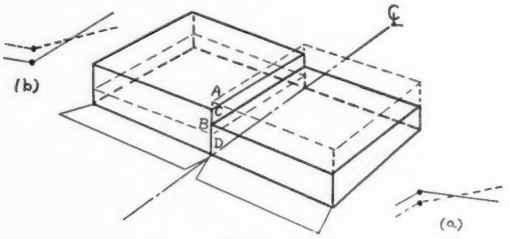


FIG. 9.
$V > V_r$.

FIGS. 6-9.
Diagrammatic illustration of the loss of lateral control at high speed due to wing twist.

given lateral movement of the control column, to something less than what would have been obtained had the aileron movement not affected the wing incidence.

This effect is illustrated diagrammatically in Figs. 6 to 9. It is assumed for simplicity that we can represent the rolling moment by constant spanwise and chordwise ordinates and that the ailerons extend the full length of the wing semi-span. Fig. 6 shows the condition for stable symmetrical flight, with zero aileron angles and equal rolling moments on each wing.

In Fig. 7 the starboard aileron has been moved down and the port aileron up and the direct effect is indicated by the dotted lines, giving rolling moments represented by A and D. The effect of the twisting moment produced by the aileron on the wing incidence is shown at (a) and (b) and the resultant rolling moments applied are those given by the full lines, represented by B and C. Thus, due to the elasticity of the wings, the final rolling moment is BC in place of AD.

Now the torsional stiffness of the wing is invariant with speed, but the aerodynamic loads vary as the square of the speed and consequently the amount of wing twist corresponding to a given aileron angle increases with the speed and eventually a speed is reached when the negative effect due to the wing twist just balances the positive effect of the ailerons. This is indicated in Fig. 8 where the effective rolling moment BC is zero. The aileron control is thus quite ineffective, and this speed at which complete loss of lateral control occurs is the critical reversal speed of the wing, or the aileron reversal speed, denoted by V_r. At higher speeds than this, as indicated in Fig. 9, the rolling moment due to the ailerons is actually reversed.

If these speeds were within the speed range of an actual machine the trouble would first be noticed by a tendency to sluggishness in answering the aileron controls, then as the speed increased there would be practically no lateral control irrespective of the amount of aileron applied, and at higher speeds actual reversal of the control would occur. Such cases have been observed in practice.

For an aeroplane with wings of sufficiently high torsional stiffness the wing twist accompanying aileron displacement would be relatively small at normal flight speeds and the rolling moment produced would approach that which would have been obtained if the wings had been rigid, and it should be one object of the designer to ensure that the torsional rigidity of the wings is such as to place the critical reversal speed at a reasonable margin above the highest speed at which the aeroplane is expected to fly.

§5.2. Accurate Analytical Determination of Critical Reversal Speed.

For a rigid wing the rolling moment $L(\xi)$ produced by a small aileron displacement ξ can be expressed in the form

$$L(\xi) = k_\xi \xi \rho V^2 s^2 c_m \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

k_ξ is then a non-dimensional coefficient of constant value for that wing, *i.e.*, independent of speed and aileron angle.

For the real elastic wing we can write similarly

$$L'(\xi) = k'_\xi \xi \rho V^2 s^2 c_m \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where $L'(\xi)$ is the effective rolling moment, allowing for the loss due to the wing twist; thus the non-dimensional coefficient k'_ξ will not be constant, but will, for a normal wing aileron combination, decrease with increase of speed V and become zero at the critical reversal speed, where the effective rolling moment vanishes. Curves of k_ξ and k'_ξ are shown in Fig. 10.

Thus, to determine V_r for a given wing it is necessary to obtain the effective rolling moment speed curve for any convenient aileron angle. The critical reversal speed is then given by the intersection of this curve with the V-axis (Fig. 10). Since the part of interest is that in the neighbourhood of the reversal speed this can be obtained by finding the values of k'_ξ for two or three speeds known to be of the order of V_r.

The first speed V_1 to take is that obtained from the simple approximate method given later. For this speed some arbitrary curve of wing twist along the span, say linear (θ_1, Fig. 11) is taken, and some small aileron displacement, say 5°, and the corresponding aerodynamic loading determined. The wing twist produced by this loading can then be found from the known elastic properties of the wing and this curve (θ_2, Fig. 11) gives a second approximation for the twist of the wing for the conditions relating to the speed V_1.

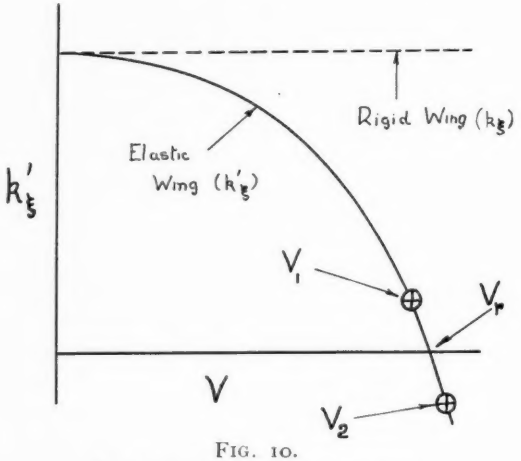


FIG. 10.
Rolling moment—speed curves.

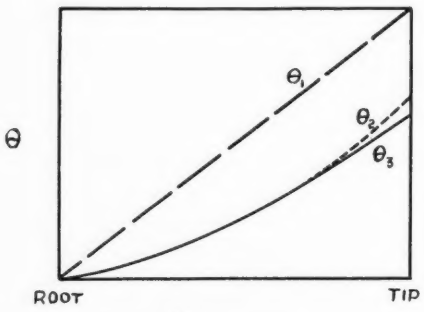


FIG. 11.
Spanwise distribution of wing twist.

Starting with the twist curve θ_2 a new loading is found and a further twist curve θ_3. This process is repeated until successive curves of wing twist are obtained which differ by only a negligible amount. Three approximations are usually sufficient. The final lift distribution and thence the effective rolling moment $L'(\xi)$ are then calculated and the corresponding coefficient k'_ξ is thus obtained for the speed V_1. If k'_ξ is found to be positive then a higher speed V_2 is taken and the above process repeated.

In most cases two speeds are usually sufficient to define the $k'_\xi - V$ curve in the region where it crosses the axis, and at the worst, only one more speed would require consideration.

This procedure to determine the critical reversal speed is accurate and is applicable to any kind of wing.

§5.3. Experimental Determination of Critical Reversal Speed.

The critical reversal speed of a given wing can be obtained experimentally from wind tunnel tests. It is not necessary to make measurements of the actual rolling moments on the wing as the reversal speed can be obtained from the simple observations of the wing deflections.

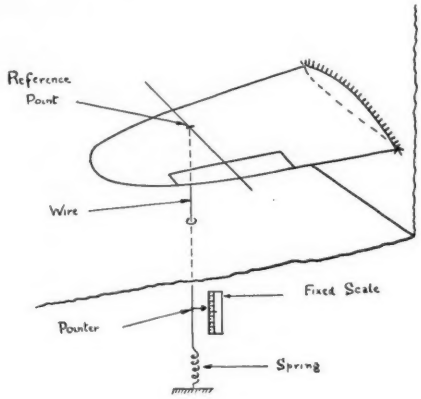


Fig. 12.

Experimental determination of critical reversal speed.

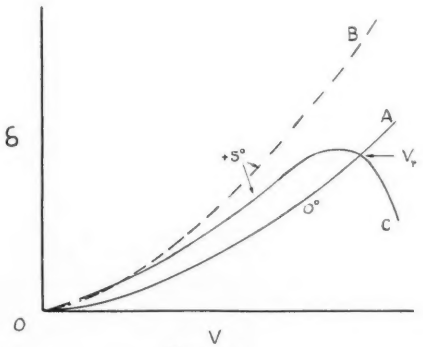


Fig. 13.

Flexural displacement—speed curves.

The wing is held rigid at the root as indicated in Fig. 12. A wire, connected to the flexural centre of the tip or mid-aileron section, passes through a hole in the floor of the tunnel, and is anchored through a helical spring. This wire carries a pointer moving over a fixed scale. The wing is held at some small incidence and measurements of the flexural displacements are made for a series of wind speeds and aileron angles.

Considering first the actions on the wing when the aileron angle is zero. As the air speed increases the increase of aerodynamic load gives a curve OA of Fig. 13 of flexural displacement δ at the chosen reference point.

For some fixed aileron angle, say $+5°$, and supposing the wing effectively rigid in torsion, then a curve such as OB would be obtained.

For the actual elastic wing, since the increase of lift due to the aileron is opposed by decrease due to the resulting twist of the wing, the resulting curve is OC. At the reversal speed V_r, there is no increment of lift and thus the additional aerodynamic load due to the aileron is equivalent to a pure couple which produces no additional displacement of the flexural centre. Thus the point of intersection of the curves OC and OA give the critical reversal speed V_r.

This is repeated for various aileron angles, and a typical set of curves obtained as shown in Fig. 14; these pass very nearly through one point giving the mean value of V_r.

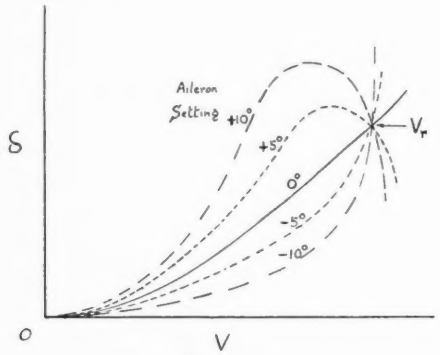


FIG. 14.

Typical flexural displacement—speed curves.

§5.4 APPROXIMATE ANALYTICAL DETERMINATION OF CRITICAL REVERSAL SPEED.

It is seen that the accurate methods for obtaining the critical reversal speed of a given wing aileron system are laborious and also require a detailed knowledge of its structural and aerodynamic characteristics. It is thus clearly desirable that a simpler method is required for finding the critical reversal speed or, alternatively, of finding the torsional stiffness which must be provided to avoid undue loss of lateral control at high speeds, which can be applied in preliminary stages of design.

The simplification of the accurate analytical procedure is made by using the " semi-rigid wing " device. As already explained, in such a wing the deflection curve is chosen at the outset and is independent of the distribution of the aerodynamic load, and thus the successive approximation process to find the curve of wing twist, just described for the real elastic wing (§5.2), does not arise, and a direct and simple formula for the critical reversal speed is obtained. This is

$$V_r = K\sqrt{(m_\theta/\rho s c_m^2)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where m_θ = torsional stiffness of wing at the chosen reference section.

ρ = air density.

s = distance from wing root to wing tip.

c_m = mean wing chord,

and K is the " reversal coefficient," and depends upon

(*a*) Position of reference section.

(*b*) Plan form and aerodynamic characteristics of wing and aileron.

(*c*) Distribution of wing twist along the span.

For most practical cases K can be written in the simple form

$$K = \sqrt{(-k_\xi/b_2 k_\theta)} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where k_ξ, k_θ and b_2 are defined by

$$k_\xi = (1/s^2)\int_{\gamma_1 s}^{\gamma_2 s} (a_2/a_1)\, a_0\, (c/c_m)\, y dy \quad . \quad . \quad . \quad . \quad (7)$$

$$k_\theta = (1/s^2)\int_{0}^{s} a_0\, (\theta/\theta_n)\, (c/c_m)\, y dy \quad . \quad . \quad . \quad . \quad (8)$$

$$b_2 = -(1/s)\int_{\gamma_1 s}^{\gamma_2 s} m\, (\theta/\theta_n)\, (c^2/c_m{}^2)\, dy \quad . \quad . \quad . \quad . \quad (9)$$

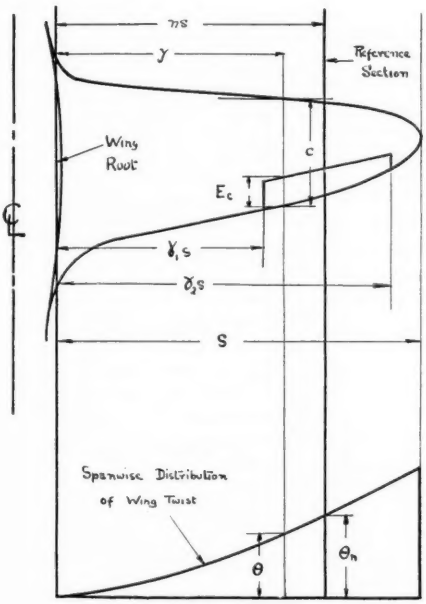


FIG. 15.
Diagrams illustrating notation.

The terms s, $\gamma_1 s$, $\gamma_2 s$, c, θ and θ_n being as shown in Fig. 15, c_m is the mean wing chord and the coefficients a_2/a_1 and m are defined by the equations for the two-dimensional aerofoil section

$$k_L = a_1 \alpha + a_2 \xi \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$k_m = -\tfrac{1}{4} k_L - m\xi + k_{mo} \quad . \quad . \quad . \quad . \quad (11)$$

k_m is taken as referring to moments about the leading edge of the wing, and a_0 is the value of $\partial k_L/\partial \alpha$ for infinite aspect ratio.

The theoretical values of a_2/a_1 and m have been worked out by Glauert for an aerofoil with a simple hinged flap and depend upon the value of E, the ratio of the flap chord to the total wing chord. The relation between $\sqrt{(a_2/a_1 m)}$ and E is given later in Fig. 29.

For a rectangular wing with a rectangular aileron, both of constant section, in which the spanwise curve of wing twist is linear, K reduces to the simple expression.

$$K_{\text{Rect}} = n\sqrt{(3a_2/ma_1)} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where n defines the reference section at ns from the wing root. For other wing plan forms K can be found directly from expressions (6), (7), (8) and (9). It is possible, however, to obtain for wings with linear taper, generalised curves for the expression $K\sqrt{(a_1 m/a_2)}$ for various ratios of tip chord to root chord and different aileron spans (Fig. 28). The product of this expression and $\sqrt{(a_2/a_1 m)}$ of Fig. 29 gives the required value of K.

§5.5. Choice of "Semi-Rigid" Wing for Critical Reversal Speed.

It has been pointed out that the success of a semi-rigid wing depends upon the choice of its representative shape of deformation and the reference section at which it is given a stiffness equal to that of the real wing.

In the problem of the loss of lateral control due to wing twist the choice has been made empirically by comparing the results obtained by the accurate procedures (analytical and experimental) with those of the approximate "semi-rigid" theory for a number of wings. Three laws of wing twist (linear, parabolic and cubic) were considered and two positions of the reference section (mid-aileron and equivalent-tip) and the comparison led to the conclusion that the critical reversal speed for a reasonably normal wing can be obtained to a good degree of approximation (3 per cent.) from its "semi-rigid" counterpart if

(1) The law of spanwise distribution of wing twist is linear.

(2) The reference section is at the mid-span of the aileron.

For a two-spar elastic wing of constant section in which torsional distortion is resisted purely by differential bending of its spars the law of wing twist is cubic. For a constant section tube of constant shell thickness the twist curve is linear. In the case of a "general" wing the combined effect of spars, cover and ribs result in a law of twist lying somewhere between linear and parabolic, and since good results are obtained when a linear law is used for the "semi-rigid" counterpart there appears no objection to taking the simplest form.

As already mentioned in §3.3, the choice of the mid-aileron as reference section has been justified by another method of choice.

§5.6. Factors Influencing Critical Reversal Speed.

It is clear that to prevent undue loss of lateral control at high speeds due to wing twist the critical reversal speed should be well above the maximum speed of flight. The effect of the various factors that the designer can control to obtain this condition can be studied by means of the simple approximate formula

$$V_r = K\sqrt{(m_\theta/\rho s c_m^2)}.$$

§5.61. Torsional Stiffness of Wing.

It is immediately obvious that the critical reversal speed varies directly as the square root of the torsional stiffness of the wing structure and the advantage of high torsional stiffness is apparent.

§5.62. Wing Plan Form.

Another very important factor is the wing plan form. If we imagine a given monoplane wing structure and superimpose upon it wing plan forms of varying degrees of taper, but of the same span and area (and hence the same aspect ratio and mean chord) the reversal coefficients of the wings so formed vary with taper (illustrated diagrammatically on the right) as shown in Fig. 16. The values relate to a wing of aspect ratio 6 with an aileron whose span is 0.5 wing span and chord 0.25 of the total wing chord. In Fig. 16 is also shown the values of

(K tapered)/(K rectangular) ($=r_k$) for the range of R considered. This curve indicates the advantage of a high degree of taper in plan form in designing to prevent loss of lateral control at high speeds; assuming that two wings, alike in all other respects, have tip chord-root chord ratios of 0.3 and 1.0, and have the same torsional stiffness at mid-aileron, then the critical reversal speed of the highly tapered wing would be about 40 per cent. greater, or conversely, for the same reversal speed the stiffness of the tapered wing could be reduced by 30 per cent.

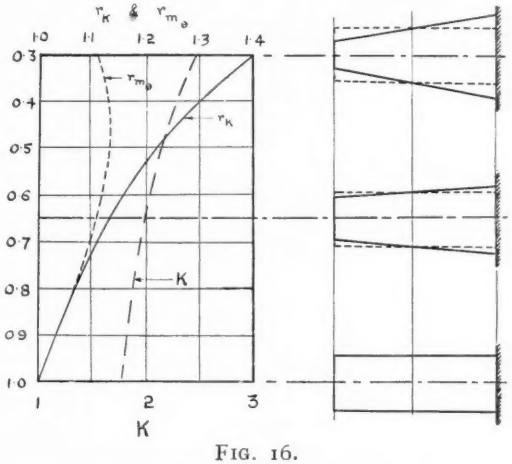


FIG. 16.

Effect of wing plan form on reversal coefficient and wing stiffness.

It might at first sight appear that it would not be possible to maintain the same torsional stiffness at mid-aileron for the two wings, to take full advantage of the 40 per cent. increase in reversal speed due to wing taper, but a simple example shows that actually the reverse can occur. If we assume that the torsional strength of the wings lies in the cover and that the stiffnesses can be estimated by Batho's formula, and taking the thickness of the cover the same for both wings and constant along the span, and the depth of the section as proportional to the local chord, then the ratio of the torsional stiffnesses for the tapered and rectangular wings (m_θ tapered)/m_θ rectangular)$=r_{m\theta}$ against R is as shown in Fig. 16, indicating that an increase of 14 per cent. in stiffness can be obtained for $R=0.45$, and, for the case under consideration, namely, $R=0.3$ the increase in stiffness as measured at the mid-aileron is 11 per cent.

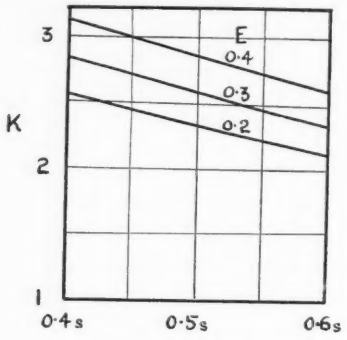
Dr. Lachmann, in his R.Ae.S. lecture of last October, also showed, by a different method, that high taper ratios offer definite structural advantage from the point of view of torsional stiffness.

§5.63. AILERON SPAN AND CHORD.

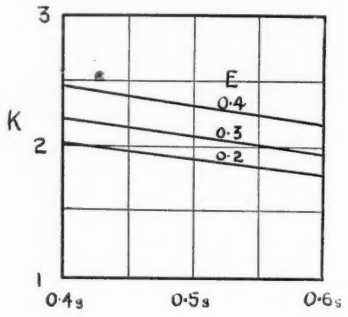
The effect of aileron span and chord on the reversal coefficient K is shown in Figs. 17, 18 and 19. These figures refer to linearly tapered wings of three-tip chord-root chord ratios, 0.30, 0.65 and 1.00, and constant aspect ratio 6.

It is seen that K increases as the aileron span decreases and increases with increase of aileron chord expressed by E, the ratio of aileron chord to total wing chord. This combination is ideal and shows the superiority of a short fat aileron over a long thin one, since an increase of K is obtained in both directions. For example, considering a wing whose tip chord is 0.3 root chord and aileron area one-eighth wing area, as shown in Fig. 20.

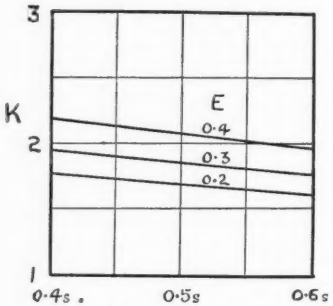
If we replace an aileron whose span is 0.6 of the wing semi-span by one whose span is 0.4 then the increase in K is 33 per cent. For a rectangular wing (Fig. 21) this would be 21 per cent. If the ratio of aileron area to wing area was one-tenth the corresponding values would be 29 and 18 per cent. Unfortunately, however, considerations of aileron effectiveness, as described later, indicate the advantage of an aileron span of the order of 0.7 s; also considerations of control operating forces and aerodynamic efficiency further complicate the problem of deciding upon the best aileron span, but an aileron span of 0.5 s



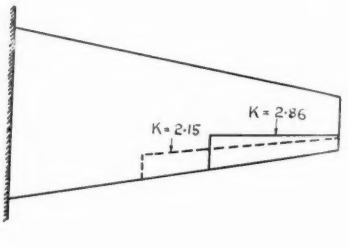
Aileron span.
$R = 0.30$.
FIG. 17.



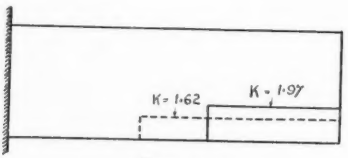
Aileron span.
$R = 0.65$.
FIG. 18.



Aileron span.
$R = 1.00$.
FIG. 19.



$R = 0.3$.
FIG. 20.



$R = 1.0$.
FIG. 21.

Effect of aileron span and chord on reversal coefficient.

can be adopted without great loss of aileron effectiveness and this seems to be the most reasonable under all-round considerations. The effect of aileron span on K is more marked for small values of R, as shown in Fig. 17. The effect on the rectangular wing of Fig. 19 being only small.

§5.64. Skewed Ailerons.

Taper of the aileron in plan form has very little influence on K, provided the aileron chord at the mid-span of the aileron remains unchanged. This is shown in Figs. 22 and 23, which refer to wings of aspect ratio of 6 in which the ratio of aileron chord to wing chord at the mid-aileron is 0.25. These results show that the variation in K for the rectangular wing considered is less than 2 per cent., and 6 per cent. for the elliptic wing. Thus a tapered aileron may be replaced by one having a constant ratio of aileron chord to wing chord, measured at the mid-aileron.

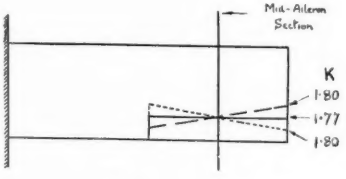


Fig. 22.

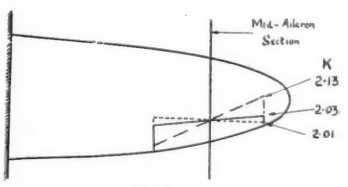


Fig. 23.

Effect of aileron plan form on reversal coefficient.

§5.65. Balanced Ailerons.

The values of K given in Figs. 17, 18 and 19 are appropriate to values of E for a simple hinged flap. For a balanced aileron these values are reasonably accurate if E is based on a flap chord equal to the distance from the hinge line to the trailing edge. This gives an approximation to the effect of aerodynamic balance on reversal speed. Considering an aileron whose total chord is 0.25 of the wing chord, with 25 per cent. balance area, then the reduction in K is of the order of 5 per cent.

§5.66. Minor Factors.

It has been shown experimentally that such factors as

(1) Position of aileron control lever, and
(2) Influence of aileron gap,

are unimportant.

§5.7. Simple Approximate Estimation of Critical Reversal Speed.

A rapid approximation to the critical reversal speed of a given wing can be obtained by simplifying the approximate " semi-rigid " theory still further. This is done by considering an " equivalent linearly tapered wing," which is a wing of the same span and area, and having the same wing chord and aileron chord at the mid-aileron section. Comparison of the coefficients obtained by this substitution, for an elliptic wing with various aileron spans, and an irregular wing is shown in Figs. 24 to 27.

The extreme underestimation of the reversal speed by the substitution of the equivalent linearly tapered wing is 9 per cent. for the wings considered and to this order of accuracy the following rapid approximation can be used to obtain the reversal coefficient.

(1) Obtain the tip chord-root chord ratio for the equivalent linearly tapered wing. This is given by the formula

$$R_{\text{E.L.W.}} = (2n-1)/(n-\tfrac{1}{2}c_{\text{M.A.}}/c_{\text{m}})-1 \quad . \quad . \quad (13)$$

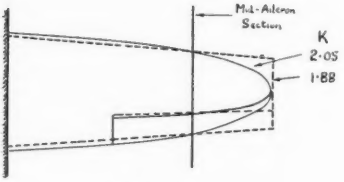


FIG. 24.

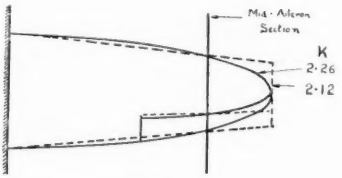


FIG. 25.

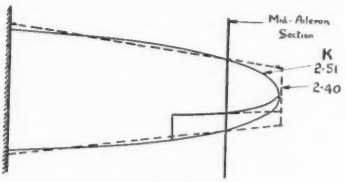


FIG. 26.

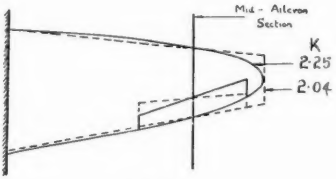


FIG. 27.

Comparison of reversal coefficients of actual and equivalent linearly tapered wings.

where n = distance from wing root to mid-aileron section, as fraction of distance from wing root to wing tip (s).

c M.A. = wing chord at mid-aileron section.

c_m = mean wing chord.

(2) Read off the value of $K\sqrt{(a_1 m/a_2)}$ from Fig. 28 appropriate to this value of $R_{\text{E.L.W.}}$ and the aileron span, expressed as a fraction of s.

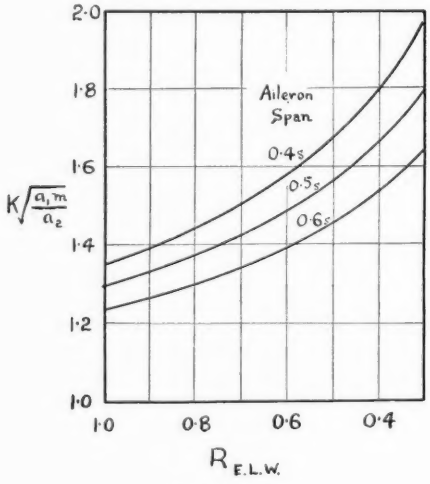


FIG. 28.

Variation of $K\sqrt{(a_1 m/a_2)}$ with aileron span and wing taper for linearly tapered wings.

(3) Obtain the ratio $E_{M.A.}$ of the actual aileron chord to the total wing chord at the mid-aileron section. If the aileron is of the simple hinged flap form then the corresponding value of $\sqrt{(a_2/a_1 m)}$ is given in Fig. 29. As already stated, for a balanced flap these values are reasonably accurate if $E_{M.A.}$ is based on a flap chord equal to the distance from the hinge line to the trailing edge.

(4) The value of the reversal coefficient K is then given by the product of

$$K\sqrt{(a_1 m/a_2)} \text{ and } \sqrt{(a_2/a_1 m)}$$

and the critical reversal speed in ft./sec. by

$$V_r = K\sqrt{(m_\theta/\rho s c_m^2)}$$

where m_θ = torsional stiffness of wing as measured at the mid-aileron section (lb. ft./radian) and ρ is measured in slugs/ft.^{3} and s and c_m in ft.

This approximate method should not be used if :—

(*a*) The plan form of the wing or aileron is decidedly irregular (*e.g.*, an aileron with a horn balance).

(*b*) The aileron aerodynamic characteristics vary very seriously along its span.

(*c*) There is a considerable distance between the outer end of the aileron and the wing tip.

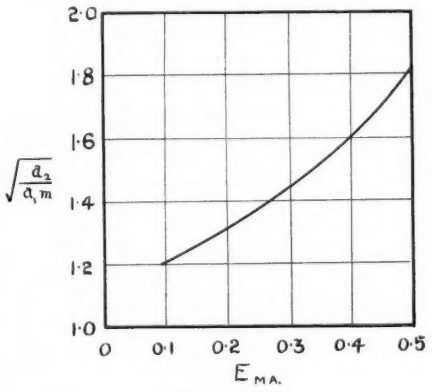


FIG. 29.

Variation of $\sqrt{(a_2/a_1 m)}$ *with aileron chord-wing chord ratio.*

In these cases or whenever greater accuracy is required, K should be calculated directly from the formulæ $K = \sqrt{(-k_\xi/b_2 k_\theta)}$ where k_ξ, k_θ and b_2 are as previously given.

§5.8. Relation between Critical Reversal Speed and Maximum Speed.

The fact that the critical reversal speed should be above the maximum speed at which a given monoplane is expected to fly, in order that there may be no chance of undue loss of lateral control, has already been stressed and the various ways in which the critical reversal speed can be raised have been considered. It is now necessary to find a relationship between V_r, the critical reversal speed and V_h, the maximum speed at which the aeroplane is expected to fly, which will ensure satisfactory lateral control at high speeds (as far as the effects of wing twist are concerned) and yet fix some definite minimum excess of V_r over V_h so that the designer need not provide excessive stiffness at the expense of added

weight. This has been done by considering the effectiveness of the aileron, in terms of a quantity called " aileron power," at various speeds up to the critical reversal speed. This aileron effectiveness must not be confused with aileron efficiency which implies ratio of effective force at the aileron to the operating force at the control column; aileron effectiveness is, as the term " aileron power " suggests, the measure of the ability of the aileron to produce a given amount of rolling velocity in a given time. For a rigid monoplane, the " aileron power " is directly proportional to the air speed V. For an elastic monoplane, since complete loss of lateral control takes place at the reversal speed the " aileron power " must become zero there, and since the amount of wing twist and its effects tend to vary as the square of the flight speed, then the " aileron power " for the rigid monoplane will be reduced, due to the elasticity of the wing, by the factor

$$(1 - V^2/V_r^2)$$

and thus we can write for an elastic wing

$$P = kV\,(1 - V^2/V_r^2) \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where P is the " aileron power " and k is a constant for any given wing aileron system.

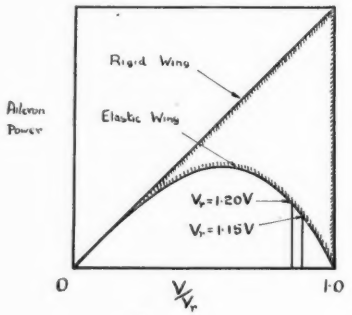


FIG. 30.

Variation of aileron power with speed.

Fig. 30 shows the variation of " aileron power " with speed, and it is seen that for a given wing aileron system, it reaches a maximum value when

$$V = V_r\,(1/\sqrt{3}) \quad . \quad . \quad . \quad . \quad . \quad (15)$$

or approximately at 60 per cent. of V_r, and finally becomes zero at the reversal speed. The shaded area of Fig. 30 represents the loss of " aileron power " due to the twisting of the wing. This diagram also shows that if V is of the order of 0.85 V_r then the effectiveness of the ailerons is about 50 per cent. of the maximum power for the elastic wing. This gives the required relationship between V_r and V_h, namely, that if the critical reversal speed is not less than 15 or 20 per cent. above the maximum speed of flight, then the aileron effectiveness will not fall below 50 per cent. of its maximum value.

§5.9. Alternative Prevention of Loss of Lateral Control.

The nature of the phenomenon of the loss of lateral control at high speeds due to wing twist has been described and the various means considered which can be used to ensure that the critical reversal speed lies at a satisfactory margin above the highest speed at which the aeroplane is expected to fly. An alternative prevention would be to provide some form of lateral control which applies a moment which twists the wing so as to increase that applied moment, or more

preferable, considering other problems involving wing stiffness, a control which applies a rolling moment without twisting the wing, *i.e.*, applies its increment of lift at the centre of pressure of the wing instead of near the trailing edge. Unfortunately, no completely satisfactory device of this kind has yet appeared, although types have been and still are being, tried.

§6. Divergence Speed.

§6.1. Nature.

When an aeroplane is in stable symmetrical flight the aerodynamic loads on the wings distort them until a position of equilibrium is reached between the external aerodynamic loading actions and the internal elastic restoring actions. If, due to some cause, the wing receives an additional small torsional deformation, the resulting elastic torsional restoring actions will tend to make the wing return to its original position of equilibrium, but the increased deformation will introduce further aerodynamic torsional actions. If the latter are greater than the restoring actions and of opposite sign, then the wing twist will increase and the forces consequent upon this additional twist may be again such as to cause still more twist and so on. If the rate of increase of aerodynamic twisting moment is less rapid than the rate of increase of elastic torsional resistance, final equilibrium is theoretically possible though it may be outside the elastic limit of the structure. If, however, the rate of increase of the aerodynamic torsional moment exceeds, however little, the rate of growth of elastic resistance, no equilibrium is possible and a state of divergence is reached involving certain failure.

§6.2. Accurate Analytical Determination of Critical Divergence Speed.

The accurate procedure for the determination of the critical divergence speed follows on lines similar to that for reversal speed. Taking a speed V_1 obtained from the simple approximate method given later, the aerodynamic loading distribution corresponding to rigid wings can be calculated, and from this loading, knowing the elastic characteristics of the wing, a first approximation to the deformation curve is obtained. Using the aerodynamic loading distribution corresponding to this deformation a new distortion curve is found, and so on. If the speed V_1 is less than the accurate critical divergence speed then the successive deflections will decrease, otherwise they will increase.

As in the case of critical reversal speed this method requires a detailed structural and aerodynamic knowledge of the wing.

§6.3. Approximate Analytical Determination of Critical Divergence Speed.

The use of the " semi-rigid " wing device in the problem of wing divergence leads to the simple approximate formula

$$V_d = D\sqrt{(m_\theta/\rho s c_m^2)} \quad . \quad . \quad . \quad . \quad (16)$$

For a rectangular wing of constant section in which the twist curve is linear the " divergence coefficient " D reduces to the very simple expression

$$n\sqrt{(3/a_1 e)} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

if it is assumed that the moments can be assessed by strip theory e is a constant defining the aerodynamic centre of a wing section as a distance ec from the flexural centre, and is assumed constant along the span, n defines the reference section as ns from the wing root.

At the present stage of the work on divergence no work has been carried out to find the most suitable spanwise position of the reference section to be used in the semi-rigid theory. This can be done on lines similar to those of reversal speed, *i.e.*, by finding the accurate values of the divergence speed, either by the laborious procedure or by experiment, and comparing the results with the approximate values from the semi-rigid theory for two or three choices of reference

section, taking a reasonably representative shape of deformation for the spanwise curve of wing twist.

§6.4. Factors Influencing Critical Divergence Speed.

The effect of the various factors influencing the divergence speed of a wing can be studied by means of the simple approximate formula

$$V_d = D\sqrt{(m_\theta/\rho s c_m^2)}.$$

§6.41. Torsional Stiffness of Wing.

To obtain a high value of the critical divergence speed the obvious advantage of high torsional stiffness is apparent.

§6.42. Wing Plan Form.

Another very important factor is the wing taper in plan form. If we superimpose upon a given wing structure plan forms of varying degrees of taper, of the same span and area the critical divergence speeds of the wings so formed vary with taper as shown in Fig. 31. These values refer to linearly tapered wings of

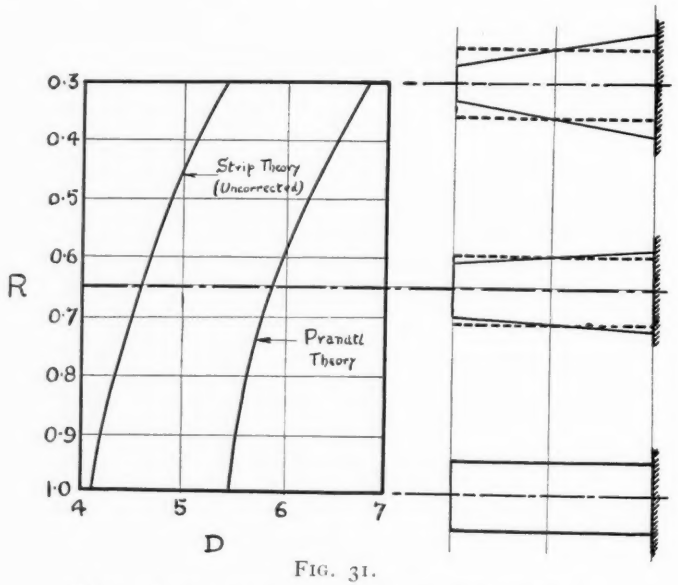


Fig. 31.

Effect of wing plan form on divergence coefficient.

aspect ratio 6, in which it is assumed that the aerodynamic centre is 0.05 of the chord from the flexural centre all along the span (*i.e.*, $e = 0.05$ c). The reference section has been taken at 0.75 of the span from the root ($n = 0.75$) and the slope of the lift curve as 2 ($a_1 = 2$). In the case of critical reversal speed it was found that the reversal coefficient K could be estimated by strip theory with a small correction, which is negligible in normal cases, but for the divergence coefficient D, strip theory overestimates by about 30 per cent.; actually in the example of Fig. 31 the excess was 33 per cent. for a tip chord-root chord ratio of 1 and 26 per cent. for 0.3.

Fig. 31 shows that for two wings, alike in all respects except for taper in plan form, with tip chord-root chord ratios of 0.3 and 1.0, and the same torsional

stiffness at the reference section the critical divergence speed of the highly tapered wing would be about 25 per cent. greater.

§6.43. Flexural Centre and "Quarter Chord" Point.

The simple expressions for the divergence coefficient

$$n\sqrt{(3/a_1 e)} \text{ for a rectangular wing,}$$

$$n\sqrt{(3/a_1 e)}\, f(R) \text{ for a tapered wing, where } R = \text{tip chord/root chord,}$$

show that a small value of e makes for high divergence speed, *i.e.*, a position of the flexural centre close to the aerodynamic centre at all wing sections, *i.e.*, the flexural centre should be near the quarter chord point from the wing leading edge.

§6.5. Relation between Reversal and Divergence Speeds.

It can be shown that for most wing aileron systems the divergence speed just described always occurs at a higher speed than the critical reversal speed. If, however, the aileron is balanced aerodynamically, then it is possible for V_d to fall below V_r. In this case, the adverse effect could be eliminated by the use of an irreversible aileron control, or alternatively making the aileron circuit of high stiffness.

§7. Wing Futter.

§7.1. Nature.

The phenomenon of flutter, conveniently described as the more or less irregular oscillation of some part of the aeroplane, has received much attention in the past few years. For the normal wing aileron system with its three degrees of freedom:—

(1) Flexural motion of wing.
(2) Torsional motion of wing.
(3) Oscillating motion of aileron about its hinges four types of flutter are possible:—
  (*a*) Flexural aileron, involving wing flexure and aileron oscillation;
  (*b*) Torsional aileron, wing torsion and aileron oscillation;
  (*c*) Flexural torsional, wing flexure and torsion; and
  (*d*) Flexural torsional aileron, involving all three degrees of freedom.

The first three of these types of flutter are termed binary and the last ternary.

§7.2. Analytical Determination of Critical Flutter Speed.

A completely accurate method for the determination of the critical flutter speeds of a given wing aileron system is not available and even when the problem is reduced to its simpler form by the substitution for the real elastic wing of its semi-rigid counterpart the procedure, due to the elaborate series of the tests and calculations required, is still too laborious and expensive for routine use.

It was, however, possible to deduce from the semi-rigid theory, certain design recommendations, some precise statements, others of a qualitative nature. Among the latter was the recommendation "All elastic stiffnesses as large as possible," and so as to extend the value of this statement, the problem of the preclusion of the two binary wing aileron flutters was attacked by a statistical method. This provided criteria for the flexural and torsional stiffnesses of the wing in the following forms:—

$$\text{Flexural criterion } (1/V_h)\sqrt{(l_\tau/d^3)} \quad . \quad . \quad . \quad (18)$$

$$\text{Torsional criterion } (1/V_h)\sqrt{(m_\theta/dc_m^2)} \quad . \quad . \quad (19)$$

where l_τ and m_θ are the flexural and torsional stiffnesses of the wing, already defined and measured in lb. ft./radian, and

c_m = mean chord of wing (ft.).
d = distance from wing root to the "equivalent tip" section (ft.).
V_h = maximum speed to which the aeroplane is expected to fly (ft./sec.).

These criteria were evaluated at both the " mid-aileron " and " equivalent tip " sections and by comparison with aeroplanes which were known to be immune from wing aileron flutter it was possible to define certain minimum values of these criterion.

With regard to flexural torsional flutter, or pure wing flutter as it is termed (incidentally, more rare than wing aileron flutter), the effect of the wing elastic stiffnesses has been investigated by considering the flutter speed of a typical cantilever wing.

More recent work on wing flutter has been in connection with work begun in Germany by Kussner, who gave a semi-empirical formula for the critical speed V_k for wing instability, of the simple form

$$V_k = K_k n_k c \qquad (20)$$

where c = mean chord of the " oscillating " part of the wing.

n_k = lowest " dangerous " resonance frequency of the wing (for most cantilever wings with mass balanced ailerons this is approximately the natural frequency of the wing in torsion).

K_k = a " constant " with a value of the order of 4, which depends mainly upon the internal structural damping of the wing structure.

The value of the " dangerous " resonance frequency " n_k " and the " oscillating chord " c, and information for obtaining the approximate value of K_k, can be determined for the full-scale aeroplane by " resonance " tests, in which the machine is elastically suspended and excited by an out-of-balance motor.

It is interesting to note the form that Küssner's formula takes when we assume (as is often the case) that the " dangerous " oscillation is that in torsion. Writing the torsional moment of inertia of the wing as

$$I_p \propto c_m{}^4 s \text{ then } n_k \propto \sqrt{(m_\theta / c_m{}^4 s)}$$

and the formula can be written

$$V_f = F \sqrt{(m_\theta / \rho s c_m{}^2)} \qquad (21)$$

where V_f is the flutter speed and F the " flutter coefficient."

Küssner's formula could similarly be expressed in the form

$$V_f \propto \sqrt{(m_\theta / d c_m{}^2)} \qquad (22)$$

(since d is proportional to s) which compares with (19).

§7.3. Factors Influencing Critical Flutter Speed.

§7.31. Wing Stiffness.

Consideration of the two flutter criteria indicate the advantage of high wing stiffness both in torsion and flexure, to ensure high values of flutter speeds of the wing aileron type. The work on pure wing flutter shows that the ratio of torsional to flexural wing stiffness should be as high as possible, and that the safest way to ensure this is to provide high torsional stiffness rather than low flexural stiffness.

§7.32. Aileron.

It is seen that three of the four types of flutter involve the motion of the aileron and so if this could be prevented then the onset of the more common types of wing flutter would be eliminated. At present the most satisfactory aileron anti-flutter measure appears to be " mass balancing " of the ailerons, which provides that the product of inertia of the aileron should have a small negative value, as described in A.P. 970. In this respect it is worthy of note that balance masses uniformly distributed along the leading edge of the aileron are more effective than a concentrated bob-weight, and also that the control surface should have a high value of torsional stiffness. The development of a suitable type of irreversible control mechanism would, of course, provide a potent

alternative to mass balancing. If an irreversible control is not fitted then the aileron circuit should have a high stiffness and be free from friction.

§8. Summary.

Considering the conditions to give high values of the reversal, divergence and flutter speeds of a given monoplane wing, it is fortunate that none are in direct opposition. Reviewing the position in respect to the various factors which can be controlled during design we have:—

§8.1. Wing.

The simple approximate expressions for the various critical speeds and the two flutter criteria show the importance of high wing stiffness, especially in torsion.

The advantage of high taper in plan form has been shown, giving substantial increase of the reversal and divergence coefficients, as well as the possible increase of torsional stiffness. As far as can be estimated at present taper in plan form is not detrimental to a high flutter speed.

§8.2. Aileron.

Changes of span and chord of the aileron have the greatest effect on reversal speed, for which an aileron with short span and large chord is superior to one of long span and narrow chord.

Aerodynamic balance of the aileron has been indicated to be detrimental to divergence and reversal speeds. As regards its effect on flutter the opinion of English reports is that it is detrimental, but foreign work indicates it to be advantageous.

The discovery of a satisfactory form of irreversible aileron control mechanism would be valuable in eliminating divergence and flutter, in the absence of which a high stiffness of the control circuit and mass balanced ailerons are desirable.

Acknowledgment.

In thanking the Air Ministry for permission to read this paper, I have to point out that I take full responsibility for all statements made and opinions expressed.

Notation.

s = distance from wing root to wing tip.
ns = distance from wing root to reference section.
d = distance from wing root to equivalent tip.
y = distance from wing root to general section.
c = wing chord at general section.
$c_{M.A.}$ = wing chord at mid-aileron section.
c_m = mean wing chord.
R = tip chord-root chord ratio for linearly tapered wing.
E = ratio of aileron chord to total wing chord.
ec = distance from aerodynamic centre to flexural centre at general section.
α = wing incidence.
θ = wing twist.
ξ = aileron angle.
a_1, a_2 = defined by $k_L = a_1\alpha + a_2\xi$.
m = defined by $k_m = -\frac{1}{4} k_L - m\xi + k_{mo}$.
m_θ = torsional stiffness of wing $= T/\theta$.
l_z = flexural stiffness of wing $= Pl^2/\delta$.
V = air speed.
V_r = critical reversal speed with "reversal coefficient" K.
V_d = critical divergence speed with "divergence coefficient" D.
V_f = critical flutter speed with "flutter coefficient" F.
V_h = highest speed at which aeroplane may fly.

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ABSTRACTS FROM THE SCIENTIFIC AND TECHNICAL PRESS.

Issued by the

Directorates of Scientific Research and Technical Development, Air Ministry.

(Prepared by R.T.P.)

No. 45. JULY, 1937.

On the Wave Making Resistance and Lift of Bodies Submerged in the Water. (N. Kotchin, Trans. Conf. on Theory of Wave Resistance, Moscow, May, 1936, pp. 65-134.) (45/1 U.S.S.R.)

General expressions are deduced for the forces acting on a submerged body moving with steady linear motion under a free surface. The resulting surface waves are assumed to be so small that the usual assumptions of the wave theory may be accepted. The method worked out is based on the introduction of a special function in terms of which the wave making resistance and lift of the body can be expressed directly.

In the first place, the problem of lift and wave making resistance is discussed for the case of motion under the surface of a heavy fluid, with special reference to calculation of the changes in circulation due to the effect of the free surface.

The same problem is also discussed for a three-dimensional flow.

Accepting the first approximation, it is possible to obtain results similar to those obtained by Havelock for the motion of a sphere and of an ellipsoid. As a particular case, similar formulæ are deduced for the wave making resistance of a ship moving on the surface of a fluid.

Finally, both the two- and three-dimensional problems are solved by numerical solution of the integral equations.

The Theory of Isotropic Turbulence. (H. L. Dryden, J. Aer. Sci., Vol. 4, No. 7, May, 1937, pp. 273-280.) (45/2 U.S.A.)

The intensity and the scale form two statistical properties of turbulence which can be studied experimentally. The intensity is measured by the root mean square fluctuation of the speed and the scale by $\int_0^\infty Ry\, dy$ where Ry is the correlation between the velocity fluctuation at points a distance y apart on a line perpendicular to the mean flow.

A theory of the behaviour of intensity and scale is developed somewhat similar to that of electro-magnetic radiation. Turbulence may be described in terms of an energy distribution and wave length, and it is assumed that the former tends to a limit determined by the law of dissipation. Alternatively, if the latter is

known, the law of decay of the total energy and the change in turbulence scale can be predicted.

The author shows that satisfactory agreement with experiment can only be obtained if the dissipation is assumed to vary as the square of the velocity.

Theory of Rectangular Wings of Small Aspect Ratio. (W. Bollay, J. Aer. Sci., Vol. 4, No. 7, May, 1937, pp. 294-6.) (45/3 U.S.A.)

The theory presented differs from the conventional treatment of the subject in that the trailing vortices leave at some angle to the wing and thus do not all lie in a horizontal plane passing through the trailing edge. At the same time assumptions were made for the lift distributions which are applicable to small aspect ratios.

The present theory thus supplements the linear Prandtl theory which is more adapted to large aspect ratios.

Both asymtotic values for zero and infinite aspect ratios are correctly given and the theory holds well for aspect ratios of less than unity.

Reaction Jets with Supersonic Speeds of Flow. (J. Chalom, Comp. Rend., Vol. 204, No. 22, 31st May, 1937, pp. 1614-5.) (45/4 France.)

The increase in reaction obtained by the use of convergent-divergent nozzles has been studied. The flow was examined by means of an interferometer and the decrease in reaction at very high (supersonic) speeds was traced to the formation of reflected wave systems in the nozzle which decreased the available discharge section. It has been found that under these circumstances a diverging-converging profile for the nozzle gave better results.

Progress in Aerodynamics. (T. v. Kármán, Les Ailes, No. 836, 24/6/37, pp. 7-8.) (45/5 France.)

The following are the main points considered by v. Kármán in his recent Paris lecture:—

1. N.A.C.A. researches are in progress with the object of controlling boundary flow and maintaining its laminar character over a greater proportion of the body surface. Reference is made to photographs of the airflow over a wing of 1 m. chord, showing the laminar layer persisting for a distance of over 30 cm. from the nose.

2. Lift distribution for wings with small aspect ratio is being studied. There appears some difficulty of accounting for experimental results by an extension of the classical theory.

3. The effect of central flaps and marginal vortices on the lift distribution being investigated. An extension of the flaps over the whole wing is recommended for the landing of large aircraft with heavy wing loading.

4. Above 30,000 feet, air-cooled engines are difficult to cool and this accounts for the renewed interest in liquid-cooled engines with cowled radiators (Allison).

5. Three-wheeled landing carriages with a nose wheel are coming into favour for large machines (Douglas D.C. 4). In this arrangement the tail surfaces are kept away from the ground and this makes the control more efficient.

The Leakage of Gases through Narrow Channels. (A. Egli, J. App. Mech., Vol. 4, No. 2, June, 1937, pp. A63-7.) (45/6 U.S.A.)

By introducing non-dimensional variables, a differential equation is derived for the pressure drop of an ideal gas flowing in a parallel channel. This differential equation is integrated for the case of flow through a channel of length S, starting from rest, this being the most important case in technical applications of narrow space flow. Results are given graphically, showing in non-dimensional form the relationship between mass flow, pressure drop and frictional resistance. In addition to being a function of Reynolds number, the frictional resistance coefficient

λ depends on the aspect ratio (length of channel/clearance) and on the roughness of the channel wall; λ can easily be determined from leakage tests. Results of tests of the leakage of air and steam through the narrow clearance between a valve stem and bushing are given graphically and afford practical evidence of the use of the theory. Formulæ are derived for the calculation of the leakage of gases through reamed bushings on ground stems and expressions obtained for the leakage of liquids (incompressible fluids) as special cases of the gas formulæ.

Fluid Flow Analyser. (H. L. Parr, Engineer, Vol. 164, No. 4251, 2/7/37, pp. 24-25.) (45/7 Great Britain.)

The apparatus described has been developed in the Mechanical Engineering Department of Columbia University. It consists of a shallow glass box 12in. wide, 48in. long and $\frac{1}{4}$in. deep through which air is drawn by means of a small electric fan. The streamlines are marked by means of titanium tetrachloride jets evenly spaced across the inlet section. Models to be examined are cut out of $\frac{1}{4}$in. rubber sheet and clamped between the top and bottom of the observation box. The article is illustrated with sample photographs showing the streamline flow round various obstacles.

On the Resistance Experienced by a Body in Motion Relative to a Viscous Fluid. (V. Valcovici, Z.A.M.M., Vol. 17, No. 3, June, 1937, pp. 177-80.) (45/8 Germany.)

The difference between the resistance experienced by a body in the case of accelerated flow of a fluid, the body being at rest, and that experienced for accelerated motion of the body, the fluid being at rest at infinity, is equal to the force of inertia of the fluid displaced by the body. This theorem, originally established by the author, and confirmed by St. Neumark in a special case (Z.A.M.M., Vol. 16, No. 2, April, 1936, pp. 117-20), is proved here for the general case of curvilinear motion of a body in a viscous fluid.

Experimental Study of Transverse Stability in Flight and in a Wind Tunnel. (L. Coroller, Journées Tech. Int. Aéronaut, Paris, 1936, pp. 467-486.) (45/9 France.)

Full-scale and model tests of a Potez twin-engined low wing monoplane, of 3,000 kg. total weight, are described. Flight tests included observation of the position of either the rudder or the aileron control to maintain (1) steady rectilinear flight, (2) and (3) steady turns to the left and to the right of known angular velocity, the other lateral control being held fixed, and the tests being made over a range of speeds and with engines at fixed throttle settings (including fully open). The difference between the control positions for straight and curvilinear flight determines the degree of stability or instability for a given test speed. A wing dihedral angle of about 5° was found to give stability over the flying range of speeds. Rolling and yawing moments of a model were measured in a wind tunnel over a range of angles of yaw and incidence. A stability diagram can be obtained by plotting curves for the ratio of the rates of change of rolling and yawing moment with angle of yaw against wing incidence or aeroplane speed, the constant parameter being wing dihedral. To each dihedral angle there corresponds a speed below which instability sets in.

Trouble with Goodrich De-icers. (Inter Avia, No. 438, 5/6/37, p. 3.) (45/10 U.S.A.)

The Department of Commerce, U.S.A., after finding that parts of the wing leading edge of air liners on which Goodrich rubber de-icers had been applied, had weakened, has suggested to the air lines the removal of these devices and a thorough inspection. Improved methods of attachment are in course of development.

The Argus Wheel Brake at the Brussels Aero Show. (Inter Avia, No. 438, 5/6/37, pp. 4-5.) (45/11 Germany.)

One side of the Argus wheel, which is cast in one piece, forms a brake casing and is provided with a brake casing lid; the brake unit is located in the brake casing between the interior hub tube and the brake flange. The brake unit consists of an elastic braking element between symmetrically arranged sprung torsion discs which carry the brake linings. By forcing oil into the braking element, the brake linings are pressed against steel discs which are fastened to the brake casing. No servo apparatus is required and the braking effect is thus eased off without jamming or slipping; the brake may be used for either direction of the Argus wheel which rests on ball or roller bearings. The connecting units between the brake and the feeder tube are fitted with valves which open automatically when joined together. When the coupling is disconnected the two valves close automatically and the loss of braking oil as well as the penetration of air and dust into the feeder system is made impossible. On changing the wheel, no filling or airing of the braking system is required.

Four-Engined Land Transport Planes. (Inter Avia, No. 439, 8/6/37, pp. 1-2.) (45/12 ——.)

Modern land plane construction tends towards four-engined aircraft which is already the usual arrangement in the case of flying boats.

The following is a table of four-engined land planes now under construction or planned:—

Country.	Type.	B.H.P.	Gross Weight (tons).	Passengers.	Top Speed (as given by firm)	State of development.
Germany ...	Junkers Ju.-90	4 × 800	20	40	220/236	Undergoing trials.
France ...	Bloch 160	4 × 690	—	—	—	,, ,,
,,	Breguet 760	4 × 1100	24·5	56	236	Planned.
,,	Farman F. 223	4 × 690	—	Mail.	225	Ready for flight shortly.
,,	Farman F. 224	4 × 815	18	44	194	In service.
,,	Wibault	4 × 1300	25	73	239	Large model completed
England ...	DH. 91 Albatross	4 × 450/550	11·5	22/30	200	Undergoing trials.
,,	AW.-27 Ensign	4 × 795	20	27/42	200	Ready for flight.
Holland ...	Fokker F. 56	4 × 1100	22·5	56	220	Planned.
U.S.A. ...	Boeing 370	4 × 1205	21·5	32	—	Under construction.
,,	Curtiss	—	—	—	—	,, ,,
,,	Douglas DC.-4	4 × 950/1100	30	40	230	,, ,,
,,	Glenn Martin	—	—	40	—	,, ,,
U.S.S.R. ..	A.N.T. 20	4 × 1200	40	60	171	Ready for flight shortly.

Compressed Air, Hydraulic and Electricity Aboard Aircraft. (Ch. Waseige, Inter Avia, No. 440, 12/6/37, pp. 1-3, and No. 441, 15/6/37, pp. 1-3.) (45/13 France.)

The principal conclusions of the lecturer were as follows:—

1. *Drive.*—For the operation of electric generators, air and liquid pumps, the most fortunate solution is the installation of a separate gearbox which is engine driven through a flexible shaft. Provision is made on the box for driving the various accessories at appropriate speeds.

It has been found that a number of smaller units (such as generator or air pumps) are preferable to single units of equal capacity (increased efficiency and reduced cooling difficulties).

2. *Compressed Air.*—The use of a single air compressor with various stages of pressure reduction has not proved feasible and thus separate high pressure (30 atm.), medium pressure (2.5 atm.), and low pressure (0.5 atm.) blowers have to be provided. (The high pressure is mainly used for engine starting, brakes and shock absorbers, medium pressure for automatic steering apparatus and low pressure for de-icing.)

In addition an exhauster is now usually fitted to operate the gyro.

3. *Hydraulic Gear.*—The great latitude as to gear ratio renders the hydraulic system specially suitable for the operation of controls.

4. *Electric.*—The use of alternating current 110 volt, 150 cycles, is recommended.

Span Load Distribution for Tapered Wings with Partial Span Flaps. (H. A. Pearson, N.A.C.A. Report No. 585, 1937.) (45/14 U.S.A.)

Tables are given for determining the load distribution of tapered wings with partial span flaps placed either at the centre or at the wing tips. Seventy-two wing flap combinations, including two aspect ratios, four taper ratios, and nine flap lengths are included. Comparison between theory and experiment shows that the predictions of this report as to load distribution are sufficiently accurate for structural purposes. The data are also of interest in relation to the stalling of tapered wings with flaps. Only qualitative agreement is however to be expected, especially in the case of partial span flaps, since theory neglects the relatively large transverse flow caused by abrupt changes in lift distribution produced by the flap. This flow delays the stall of sections immediately adjacent to the flap and causes the initial stalling point to move outward away from the flap ends.

The "Pouit" Wing Flaps. (Les Ailes, No. 837, 1/7/37, p. 6.) (45/15 France.)

Immediately prior to landing, the Pouit flap acts as an ordinary high lift device, the flap being at approximately 20° to the wing chord. As soon as the aeroplane has touched the ground, the incidence of the flap is reversed so that it now makes an angle of 20° in the opposite direction. This causes the aircraft to be pressed down on to the ground by aerodynamic forces as well as gravity. The braking system is rendered more effective and the landing run is reduced considerably.

Aerodynamic Brake on Polar Aircraft. (Les Ailes, No. 837, 1/7/37, p. 6.) (45/16 U.S.S.R.)

The Russian plane A.N.T.6 which was the first to land at the pole was provided with a tail parachute, which was released as soon as the skis touched the ice. The pull of the parachute was transmitted to the central wing section and caused a considerable reduction in the landing run.

Some of Germany's New War Weapons. (U.S. Naval Institute Proceedings, Vol. 63, No. 412, June, 1937, p. 892.) (45/17 U.S.A.)

Germany is the only country which has built up an anti-aircraft organisation as an integral part of its flying force. The air force is divided into three branches :—

(1) The air force proper.
(2) Anti-aircraft defence.
(3) Signal corps, which is charged with communication duties and observation and detection of raiding planes.

The Germans use 20 mm. and 37 mm. guns as well as machine guns on double mounts for low flying planes and 88 mm. for heights of 4,000 m. and above. Co-operation between searchlight and gun is electrical, the searchlight crew controlling the gunfire. It is stated that experiments are in progress to make the sound detectors control both searchlights and guns automatically.

A new kind of bomb has been evolved with an electrostatic fuse instead of the more normal chemical percussion fuse. Until an electric condenser inside the bomb is charged, the bomb is perfectly harmless. The release mechanism renders the bomb " live " by charging the condenser and it is stated that the sensitivity to impact is much greater than that of the normal type.

Flying Searchlights (*Views of Air Defence*). (The Royal Air Force Quarterly, Vol. 8, No. 2, April, 1937, pp. 112-117.) (45/18 Great Britain.)

The proposed searchlight carriers resemble multi-seater fighters, the searchlight (high pressure mercury vapour) being carried in the nose (pusher airscrews). A crew of two is carried and the speed of the aircraft is the same as that of the accompanying fighters. The object is to show up the enemy aircraft and facilitate the attack of the fighters. It is stated that a searchlight 25 to 30 inches in diameter will have a range up to 1,500 yards. No details as to the electrical installation are given.

Ramming Attack against Bombers. (The Royal Air Force Quarterly, Vol. 8, No. 2, April, 1937, pp. 141-146.) (45/19 Great Britain.)

The suggestion is put forward to design special interceptor fighters to ram bombing aircraft with the object of carrying away the tail unit. The cockpit is placed well aft so as to enable the pilot to escape by parachute. No armament is carried, the weight saved being utilised by having an armoured bulkhead so as to deflect the bullets of the bomber. It is thought that present-day bombers will be practically defenceless against this form of attack. If carried out at high altitude, the ramming pilot has a reasonable chance to escape by parachute. In the case of low altitude bombing attack, however, the parachute is probably of little use.

Experience with Heavy Bombers in Spain. (Les Ailes, Vol. 17, No. 836, 24/6/37, p. 12.) (45/20 Spain.)

The French B.C.R. (twin-engined bombers, crew of four) of which a large number have been put into service, has failed under practical war conditions in Spain for the following reasons:—

(1) Defective armament.
(2) Lack of speed and manœuvrability.

(1) The bomber suffers from a complete lack of fire co-ordination for its three machine guns. Attempts are now being made to fit an electrical signalling system. But even if this difficulty could be overcome and the gunners kept informed of the position of the attacking fighters, the turrets as supplied are very unsatisfactory. They appear to be makeshift contrivances on which, in contradistinction say with the engine installation, very little thought and care has been expended. The motion of the turret, instead of being smooth and progressive is harsh and jerky. The transparent portions deform to such an extent that serious errors are introduced in the sighting of the gun. Theoretically, the field of fire of the bomber should possess no blind spots. In practice it was very different and the fighter soon took advantage of this.

(2) As regards the inferiority of speed mentioned above, it appears that this can be overcome by special designs such as the Potez 63. But what is the use of speed without fire accuracy Only by combining both will it be possible to hold the mastery of the sky.

Observations on Cylinder-Bore Wear. (M. M. Roensch, J.S.A.E., Vol. 40, No. 3, March, 1937, pp. 89-98.) (45/21 U.S.A.)

The main causes of cylinder-bore wear in approximate order of their importance are:—(1) *Abrasion* (wear due to foreign particles in the oil film); (2) *erosion* (wear due to metal contact between the pistons or rings and the cylinder bore);

(3) *corrosion* (oxidation or chemical attack of the cylinder wall by the products of combustion). In certain cases the relative importance of these effects may be completely changed by the conditions of operation, engine design, air cleaner design, piston and ring equipment and the lubricating oil. (1) The main cause of *abrasion* is road dust entering the crankcase or the intake system. The only real solution is to keep the dirt out by means of air cleaners; cylinder wear in presence of dust may be reduced by hard cylinder block metal and wider piston rings of suitable design and material. (2) In preventing *erosion*, design of the cylinder block and piston ring are of outstanding importance. The heavy erosion which occurs during starting up from cold, due to the fact that the piston heats and expands more quickly than the cylinder, can be improved by anodising or tin plating of the piston. (3) The worst *corrosion* occurs when an engine is cold, due to condensation on the cylinder walls. Solutions under consideration include the use of light oils which get into circulation rapidly, high jacket temperatures and adequate supply of oil.

Pateras Pescara Free Piston Compressor. (Les Ailes, No. 834, 10/6/37, p. 7.) (45/22 France.)

Although no reference is made to the fact, this compressor shown at the Paris Exhibition, works on the same principle as the Junkers free piston compressor, described in the technical Press in 1935 (Abstract No. 30,582—A. and N., No. 35, p. 21).

As already suggested by Junkers, the scheme lends itself to aircraft propulsion, the compressed air, after heating by the exhaust, being led to a number of subsidiary turbines which drive the propellers. It is stated that M. Pateras is designing a 1,200 b.h.p. unit on these lines, the overall weight being of the order of 800 gm. per b.h.p. As in the case of Abstract 30,582, no details of the coupling system are given (this is probably of the ratchet type).

Reduced Maintenance of Aircraft Engine Power Plants. (A. V. Willgoos, J. Aer. Sci., Vol. 4, No. 7, May, 1937, pp. 286-287.) (45/23 U.S.A.)

The expense of engine upkeep depends on two factors—reliability and durability. These factors in their turn depend on design, operating technique, power output, fuel and oil and overhaul technique. The outstanding improvement in design over the last ten years has been the assurance of adequate lubrication to all parts and especially to the valve gear. With the new lubrication system now available, it is possible to run engines 600 hours between overhauls without any inspection of any parts other than spark plugs (60 hours) and renewal of oil (120 hours). Attention to the last two items is likely to reduce maintenance costs considerably (better plugs and oil cleaners). At the moment operating technique still differs appreciably with different flying personnel and this reflects adversely on maintenance. With the provision of automatic carburettors this will be avoided in the future.

Low Pressure Fuel Injection System. (Aero Digest, Vol. 30, No. 6, June, 1937, pp. 46 and 48.) (45/24 U.S.A.)

The petrol injection system developed by Messrs. Marvel-Schebler Carburettors has been approved as standard equipment for the Continental W-670 engines. The article describes the system in detail with the help of a cross-sectional diagram and photographs. A single metering orifice controlled by the air throttle supplies as many pump plungers as there are cylinders. An over-riding adjustment allows for altitude control. The plungers are reciprocated by means of a swash plate, the connection being such that a simultaneous partial rotation of the plungers is produced. The spray nozzles are placed close up to the engine inlet valves and it is stated that the pick up and acceleration are both remarkably good. Three

hundred and fifty hours of winter flying without external heat and in all sorts of weather demonstrated complete freedom from icing troubles.

High Output in Aircraft Engines. (R. N. du Bois and V. Cronstedt, J.S.A.E., Vol. 40, No. 6, June, 1937, pp. 225-231.) (45/25 U.S.A.)

With the advent of high octane rated fuels, the power output of an engine can be considerably increased by a simultaneous rise in boost and compression ratio. The same high power output can be obtained either at a low boost and high compression ratio or at a higher boost and a correspondingly lower compression ratio. The low boost job will have a higher thermal efficiency, but a considerably higher explosion pressure. Although experimental single cylinder units have gone up to 1,700 lb./sq. in. (I.M.E.P. 420 lb./sq. in.) no general data as to maximum permissible pressure are available on this subject. The author calls attention to the fact that high explosion pressures are generally subject to considerable variation from cycle to cycle (probably due to changes in ionisation at the spark gap leading to variable ignition timing)* and this may affect the smooth operation of multi-cylinder units. The possibility of using pressure inhibitors (as distinct from detonation inhibitors) is envisaged. The effect of increased speed on engine output is also briefly considered. It is concluded that a cylinder which will stand the thermal and mechanical stresses due to high boost and compression ratio at normal speeds is not seriously affected by a further increase in r.p.m.

Aircraft Engine Installation Vibration Problem. (J. M. Tyler, J.S.A.E., Vol. 40, No. 6, June, 1937, pp. 252-262.) (45/26 U.S.A.)

When studying vibration problems, two types of instruments have given useful service. In the one, the structure is subjected to known impulses by means of an exciter which is attached to it. From the nature of the response, an idea of the natural frequence of the system can be formed. The second type of instrument records the actual vibrations of the structural elements as they occur in practice. Such recording is usually carried out photographically by means of electro-magnetic pick ups. A recent improvement consists in embodying an harmonic analyser in the electric amplifying circuit. This enables the amplitude to be read separately for each frequency present in the system, the operator simply copying down a meter reading. The advantage of this method over photographic or mechanical vibration recording is very great since the results are immediately available and do not depend on records being measured up or films developed. Having determined the vibration spectrum of the installation, it will be possible to predict vibration characteristics if the excitation and operating conditions are known. Until recently, discomfort in aircraft has been attributed almost entirely to propeller disturbances. With the appearance of better sound insulation, the effect of engine roughness on passenger comfort becomes more marked. The study of vibration is thus receiving an additional impetus quite apart from mechanical safety.

Compression Ignition Engine Performance at Altitude. (C. S. Moore and J. H. Collins, J.S.A.E., Vol. 40, No. 6, June, 1937, pp. 263-272.) (45/27 U.S.A.)

The tests were carried out on a single cylinder 5in. by 7in. four-cycle compression ignition engine, using a displacer piston combustion chamber. Intake and exhaust pressures were regulated by means of blowers and the temperature of the intake air (at the inlet valve) could be lowered to $-3°F.$ by passing the air over two radiators charged with solid CO_2 mixed with prestone and paraffin oil respectively. In this way atmospheric conditions both as regards pressure and temperature could be reproduced up to standard altitudes of the order of 14,000

* See also Tranlation No. 470 (Abstractor's Note).

feet. In addition tests were carried out in which the inlet air temperature and pressure and the exhaust back pressure were controlled as single variables. From the altitude tests it appears that the compression ignition engine has a slight power advantage over the carburettor engine for the same inlet temperature. This advantage is considerably increased if the carburettor engine intake has to be heated to prevent icing. It was found that the maximum performance of this particular C.I. engine followed neither a density nor an air consumption law accurately.

New Type of Engine Sleeve Valve. (Inter Avia, No. 441, 15/6/37, p. 5.) (45/28 Great Britain.)

The new valve is a short sleeve cut into four segments which reciprocate individually over the ports in the cylinder head guided by slots in the latter. The operation can be by overhead camshaft or push rod. The movement of the segments can take place before valve opening, thus allowing very rapid operation with a gentle cam profile and quite slow acceleration. Both in weight and cost the segments are an improvement on ordinary poppet or sleeve valves and cooling is claimed to be better. The guillotine valve, as it is called, would be most suitable for large bore engines in which poppet valves almost reach their limitation.

Connection between Cylinder Wear and Lubricating Oils of Different Viscosity Index; Effect of Addition of Colloidal Graphite. (E. Norlin, Tekn. Tidskr., Vol. 66, 20th March, 1937, pp. 9-16; Automobil-och Motorteknik No. 2.) (45/29 Sweden.)

A solvent-treated paraffin base oil (V.I. = 100) was compared with a mixed base oil (V.I. = 55) by tests in a Citroen type 7, 1935 model. The two oils had nearly the same viscosity at 50°C., viz., 78 and 76 centistokes respectively, and the maximum crankcase temperature was maintained throughout the tests at 40-65°C. Oil samples were withdrawn at regular intervals and inspected. At the end of the tests, measurements were made of loss in weight of the piston rings, loss in height of the piston rings and increase in diameter of the cylinder bore. The general conclusion was that the mixed base oil caused considerably more wear and produced a dirtier engine than the solvent treated product.

Comparative test runs of 200 metric miles of two Chevrolets using a highly refined paraffin base lubricating oil, alone and with addition of 4 per cent. of colloidal graphite, showed that wear was considerably greater in presence of colloidal graphite.

Cetane Numbers. (R. F. Good, J.S.A.E., Vol. 40, No. 6, June, 1937, pp. 232-242 and 251.) (45/30 U.S.A.)

The author has carried out comparative rating tests on a number of Diesel engine fuels, using both the C.F.R. engine and a full-scale single cylinder submarine Diesel engine (75 b.h.p. at 750 r.p.m.). The C.F.R. rating was carried out either by the knock meter delay method or by the critical compression ratio method. In the full-scale engine the rating was done by the ignition lag and the "computed combustion knock," both of which were obtained from indicator diagrams (special electro-magnetic indicator).

Speaking generally, correlation between the various methods was satisfactory for normal (undoped) fuels, especially in the range of low cetane numbers. In the case of doped (ethylnitrate and lead) fuels, however, the full-scale rating in cetane numbers is considerably higher than that obtained by the C.F.R. critical compression method.

The Influence of Humidity on Knock Ratings. (J. R. Macgregor, J.S.A.E., Vol. 40, No. 6, June, 1937, pp. 243-251.) (45/31 U.S.A.)

It has long been known that the amount of detonation in a spark ignition engine with any fuel decreases markedly with increase in humidity. It was, however, assumed that with the system of fuel rating normally adopted (*i.e.*, bracketing unknown fuel between two blends of reference fuel differing but slightly in knocking tendency) variation in atmospheric condition would have no effect on the result. The present experiments show, however, that the influence of humidity is not primarily the result of change in oxygen concentration, but is a specific effect depending on the nature of the fuel. Differences in knock rating of over three octane numbers were found in certain combinations of test and reference fuels when the humidity was varied over the range normally experienced in knock rating. The exact humidity to be used as standard has not yet been determined, but a water content of 0.0135lb. of water per lb. of dry air appears reasonable. The humidity in the carburettor intake is measured with a wet- and dry-bulb hygrometer and adjusted to the required value either by drying the intake air or adding steam.

The Lubrication of Journal Bearings in Oxidising Conditions. (C. Jakeman and A. Fogg, J. Inst. Petrol. Tech., Vol. 23, No. 163, May, 1937, pp. 350-366.) (45/32 Great Britain.)

It has been claimed that when lubricating oil is used under oxidising conditions in a bearing, a reduction in friction results due to so-called " activation " of the oil. The present experiments were carried out at the N.P.L. to check these claims, with the result that reduction in friction previously observed is now found to be due to mechanical improvement of the running surface with time and has nothing to do with the so-called " oxidation activity " of the oil.

Once a bush has reached the run-in condition, the " orthodox " fluid film lubrication is maintained almost up to seizure.

Substitute Fuels for I.C. Engines in Germany. (Abstracted from the German Press.) (45/33 Germany.)

The term " substitute fuel " is applied in Germany to certain gaseous fuels, such as generator gas (manufactured on the vehicle), compressed coal gas, or liquefied gas such as propane and butane carried in steel bottles. Extensive experiments have been carried out with these fuels side by side with a huge expansion in the manufacture of synthetic liquid fuels (coal hydrogenation and Fischer-Tropsch synthesis). Whilst the use of gas fuels in certain special cases may be justifiable (especially if producer gas is made from wood) the organisation required for the provision of filling stations, etc., together with the relative short radius of action of the vehicle so equipped will always severely limit the general use of " substitute fuels." Thus in 1936 only 1 per cent. of the newly registered vehicles were driven by gas. At the present moment the use of gaseous fuels is considered in Germany as a passing phase, it being hoped that the country will soon be in a position to meet all its requirements from synthetic liquid fuels.

Influence of Motor Fuel on Lubricating Oil. (A. Capetti and M. Segre, Ric. Scient., Vol. 2, 1936, pp. 403-9.) (45/34 Italy.)

By distilling various mixtures of lubricating oils and petrol or ethyl alcohol under temperature conditions similar to those obtaining in an internal combustion engine, information was obtained on the reduction in viscosity of lubricating oils as a result of crankcase dilution.

Motor Fuels. (I.G. Farbenindustrie A.G., B.P. 463, 218, 4th March, 1936.) (45/35 Great Britain.)

Fuels containing monohydric alcohols are rendered harmless to magnesium and its alloys by saturating such fuels with complex alkali fluorides soluble in them. Fluorides of the alkali metals or ammonia are claimed.

Fuel Pumps for Aeroplanes. (W. C. Clothier, J. Inst. Autom. Eng., Vol. 5, May, 1937, pp. 12-46.) (45/36 Great Britain.)

Conditions of working of aeroplane fuel pumps are discussed and examples given of typical pumps developed specially for the purpose. The effective head comprises the sum of heads due to gravity, acceleration, pipe friction and the pressure required by the carburettor. The gravity head will depend on the relative position of the engine and reservoirs. The height will commonly be 6 to 8ft. from reservoir to engine, but in large flying boats may be 16ft. The largest accelerations occur when pulling out of a dive, up to a value of 3 g., *i.e.*, a 3ft. vertical lift becomes equivalent to 9ft. while the acceleration lasts. Frictional head is due to the pipes and filters in the system and may equal several feet. Delivery pressure to the carburettor may range between 0.3 to 4lbs./in.^{2}. Other considerations are the most suitable position for the pump and the power to drive it, pump capacity, pressure control and reliability in operation. All present-day pumps are of the displacement type either (1) diaphragm, (2) piston, (3) vane, or (4) gear. (Examples of each kind are described.)

Molecular Structure and Oiliness of Lubricants. (J. J. Trillat, Rev. Gén. Sci., Vol. 48, 1937, pp. 95-107.) (45/37 France.)

Oiliness is a property specific of the interface formed between an oil and a metal rather than of the oil itself. Molecules on which the positive and negative charges are not distributed symmetrically have a permanent electrical moment and such oil molecules orient themselves on a metallic surface. This property may be given temporarily to even a paraffin hydrocarbon by placing it in an electrical field. An oily oil, *i.e.*, one whose molecules contain an active group, adheres firmly without spreading and is useful for low speed with heavy load. A paraffinic oil wets the surface and spreads, affords hydrodynamic lubrication, separates the surfaces and absorbs the heat. X-ray studies have demonstrated orientation and the gliding of one molecular layer on another. Diffraction of electrons is a more sensitive means of studying the same phenomena. When a paraffin oil containing a small addition of oleic acid was filtered through paper or glass wool, almost all the oleic acid was removed. In lubricating by wick the oil lost a good part of its active molecules by absorption on the fibres. A similar loss took place when the oil was passed over a number of steel balls; this is exactly what happens when the same oil is used to lubricate bearings or any metal surfaces.

German Fuel Regulations Revised. (Autom. Ind., Vol. 76, No. 26, 26/6/37, p. 941.) (45/38 Germany.)

A number of changes have been made recently in the regulations requiring German manufacturers of motor spirit to mix it with alcohol. By law, each manufacturer of such fuel is compelled to take from the Reich Alcohol Monopoly 10 per cent. of his sales of motor fuel in alcohol. The alcohol supplied for this purpose by the monopoly will hereafter contain one part in three (instead of one part in six) of methanol (wood alcohol).

The percentage of this mixture in motor fuel has been increased from 11 to 13-16, the rest consisting of petrol. The petrol may also be mixed with up to 10 per cent. of benzol. Mixtures of gasoline containing more than 10 and less than 30 per cent. of benzol can be sold only when a special permit has been obtained. Petrol without an alcohol addition can be sold only for aviation pur-

poses and then only if a certificate has been issued by the Minister for Air attesting the need for such fuel.

The M.T.T. Sperry Apparatus for Measuring Vibration. (G. S. Draper and others, J. Aer. Sci., Vol. 4, No. 7, May, 1937, pp. 281-285.) (45/39 U.S.A.)

The equipment records linear and torsional vibration of aeroplane structures and power plants in flight. Electro-magnetic pick-ups of small size are used and the records are photographed by means of an oscillograph. By taking simultaneous records, phase and amplitude relations can be studied.

(For the D.V.L. mechanical recorder utilising the scratch method, see translation No. 469.)

The West Telemagnetic Remote Reading Compass. (Aviation, Vol. 36, No. 5, May, 1937, p. 48.) (45/40 U.S.A.)

The compass operates a suitable indicator on the instrument board by means of electrical capacity changes. A small condenser plate is attached to the needle of the compass and two other plates to the bowl. Immediately below is placed a miniature vacuum oscillator which responds to the capacity changes and transmits the deflection to the steering indicator. Sensitivity control is provided and the indicator is unaffected by dip up to 10° to the horizontal.

The Lateral Instability of Deep Rectangular Beams. (C. Dumont and H. N. Hill, N.A.C.A. Tech. Note No. 601, May, 1937.) (45/41 U.S.A.)

Experimental and analytical studies were made of solid and hollow deep rectangular beams to study their lateral instability under various conditions of loading and restraint. The tests were made on bars and tubes of 17 S.T. aluminium alloy. Failure by lateral buckling occurred only in tests on the solid beams. It was found that, within the elastic range, the test results were in agreement with the classical theory for the lateral buckling of deep beams as given by Prandtl, Michell and Timoshenko. The tests were extended to the inelastic range where it was found that the substitution of Young's modulus by an average modulus of elasticity derived from the stress-strain curve made it possible to predict instability at high stresses.

Combined Stress Calculations. (F. R. Shanley and E. I. Ryder, Aviation, Vol. 36, No. 6, June, 1937, pp. 28, 29, 43, and 66.) (45/42 U.S.A.)

The system of determining the allowable loads under combined loading conditions put forward by the authors is called by them the " stress-ratio " method. It is non-dimensional, since it only deals with ratios and is also homologous, since the ratio must be between stresses of the same kind. The method has been applied to cases involving elastic stability, plastic stability and stress or material failure. Although the evidence is not conclusive, it appears that in many cases a single interaction curve or surface will apply to all these types of failure for a given combination of loading or stress conditions. It also seems that in certain specified cases the nature of the interaction is independent of geometrical proportions and fixity conditions. The generality of these conclusions must, however, be determined by further experiments. (Eight references.)

Rotary Fatigue—Bending Test Machine with Spring Control. (W. Spath, Z.V.D.I., Vol. 81, No. 25, 19th June, 1937, pp. 710-12.) (45/43 Germany.)

Theoretical considerations show that the results of a load test depend not only on the test bar, but also on the elastic properties of the test apparatus. For example, experiments with the Schenk fatigue bending test machine have proved that the load diagram is considerably affected by the manner in which the load is applied. Whilst most present-day machines using weight loading give very smooth diagrams and show the commencement of plastic deformation only by a

gradual change in direction of the curve, the modified apparatus, in which the load is applied by a strong spring, shows small plastic deformations with a clearly visible fall in stress. With apparatus of this kind it is therefore possible to obtain much more detailed knowledge of the processes occurring in loaded materials. Aluminium in the state of yield showed a much indented deformation load diagram, even from very low loads. The question as to whether the observed decreases in stress are directly connected with the fatigue strength cannot be decided at the present stage. In any case it is certain that a short time test carried out on a material does not necessarily give an idea of the state of the material under continuous loading.

Spring Support of the Engine Unit in Motor Vehicles and Aeroplanes. (B. Riediger, Z.V.D.I., Vol. 81, No. 25, 19th June, 1937, pp. 713-20.) (45/44 Germany.)

Vibrations caused by the unbalanced mass forces in engine units with a small number of cylinders (such as those used in road vehicles and light aeroplanes) can be counteracted by spring support of the engine. In the present paper equations are deduced for the forced vibrations, and the requisite stops are calculated. The results are not limited in any way by the size of the engine and are therefore of importance for engines of much greater power such as those in ships.

Influence of Mean Stress of Cycle Corrosion—Fatigue. (H. J. Gough and D. G. Sopwith, Iron and Steel Inst., Advance Paper, 21/5/37, 21 pp.) (45/45 Great Britain.)

Whilst much attention has been devoted to the resistance of materials to corrosion fatigue under cycles of reversed stress, no work has hitherto been carried out on the equally important practical cases of repeated or fluctuating stresses. This paper describes the results of tests under these conditions made on six aircraft materials, the behaviour of which under reversed stresses has previously been reported. These comprised a cold-drawn 0.5 per cent. C steel, three stainless steels, duralumin and a Mg. alloy containing $2\frac{1}{2}$ per cent. of Al. These were tested in air, also in a spray of 3 per cent. salt solution, under cycles of repeated and of fluctuating stresses. The results show that, as in air, the fatigue resistance of a material in a corrosive environment is considerably influenced by the mean stress of the applied cycle. As in the case of reversed stresses, no corrosion fatigue limit was indicated for any of the materials. If the range for any given endurance is plotted against the mean stress, the form of the curve obtained is in general similar to that obtained in air, using the fatigue limit in place of the endurance range.

Lux Engine Compartment Fire Extinguisher (CO_2). (Aviation, Vol. 36, No. 5, May, 1937, p. 48.) (45/46 U.S.A.)

The Lux automatic extinguisher weighs 18lb. for single, 27lb. for twin and 29lb. for a tri-motor installation. The liquid CO_2 is stored in a special light weight container and is discharged through a perforated duralumin ring surrounding the engine. A manual control is placed on the instrument board.

Globular Lightning Strikes Aircraft. (Les Ailes, No. 837, 1/7/37, p. 10.) (45/47 Australia.)

A Junkers Ju. 86 (fitted with Jumo 205 engines) was struck by globular lightning whilst flying in dense clouds at an altitude of 1,200 m. (Australia). The discharge was in the form of a sphere of light (reddish-yellow), 60 cm. diameter which formed on the nose of the aircraft. During the very short time it lasted, the cockpit was illuminated " as with magnesium flashlight."

No mechanical effect on the aeroplane was noticed in the air, but subsequent examination on the ground revealed that a small portion (approximately ½in. diameter) of the metal skin of the rudder had fused.

Medical Aspect of High Altitude Flying. (Les Ailes, No. 837, 1/7/37, p. 11.) (45/48 France.)

As military operation at altitudes between 6,000 and 10,000 m. offer important tactical advantages, it is of the utmost importance to be able to operate under these conditions. The main difficulties are physiological, and the author describes the French Medical Aviation Centre at Bourget where tests are carried out in high altitude chambers. High altitude flying requires frequent medical inspection of the pilot and a manœuvre involving rapid changes in altitudes (such as dive bombing) should not be carried out more frequently than once every five days.

It appears that 6,000 m. represents the average altitude without special oxygen. The provision of simple and efficient breathing apparatus together with training in its proper use forms one of the most important military requirements. Above 10,000 m., oxygen breathing alone is not sufficient and heights of this order and above will require either a pressure tight cabin or a special suit for the pilot.

The record stunts of to-day lead the way to practical application in future combats.

The Origin of the Noise of Air Propellers. (W. Erusthansen, L.F.F., Vol. 13, No. 12, 20/12/36, pp. 433-440.) (45/49 Germany.)

The experiments were carried out on a model propeller of symmetrical profile and zero incidence, 40 cm. diameter, which could be rotated up to 17,000 r.p.m.

The following principal conclusions were arrived at :—

(1) The pressure field near the airscrew is in satisfactory agreement with theory.

(2) The sound field can be considered as due to a series of fixed sources in the plane of rotation, the amplitude of the sources or radiators being determined only by the variation in field intensity at the point considered.

(3) Two propellers have equal sound intensity, if they are of the same diameter, same frequency, and are characterised by the same radial change in the pressure field at the same distance on both sides of the plane of rotation.

(4) Obstacles in the neighbourhood of the propeller blade increase the noise and change the directional characteristics.

(5) The note due to rotation is radiated mainly in the plane of rotation whilst the noise associated with the propeller is concentrated in the direction of the propeller axis. Change in propeller profile affects both the spectrum and the directional characteristics.

(6) If the resulting top speed is kept below 250 m./sec. the propeller makes relatively little noise.

(7) The acoustical output of the experimental propeller amounts to approximately 1 per cent. of the total propeller losses. This percentage is reduced as the top speed goes down. (Five references.)

New Aircraft Spotting Device. (Inter Avia, No. 433-4, 22/5/37, p. 13.) (45/50 U.S.A.)

Experiments have recently taken place from Fort Monmouth, New Jersey, by the military authorities with a new aircraft spotting device. The instrument is a very delicate heat detector which, through the use of infra-red rays, can trace the fastest fighting plane flying without lights and engines shut down. The machines were immediately spotted and illuminated by the ray which only shows

as a faint pencil of light along its course, but brilliantly lights up the object on which it is trained. By automatic triangulation the exact location of the object to be detected is determined within a period of 2 sec. mechanically within a range believed to be at least 20 miles. Particulars of the instrument, which is said to be of revolutionary importance, are being kept secret.

Heat Transfer During the Induction Stroke of an Internal Combustion Engine. (A. S. Stambuleanu, Z.V.D.I., Vol. 81, No. 23, 5/6/37, pp. 670-671.) (45/51 Germany.)

The experiments were carried out on a cylinder without piston, the air being admitted under pressure through the inlet valve and blown out at the open end of the cylinder. The cylinder walls were heated by an oil bath and the mean air temperature inside the cylinder was measured by a series of thermocouples. The experiment was repeated for series of valve lifts and cylinder lengths and the results show that the heat transfer coefficient α could be represented by the equation

$$\alpha = AC_p\eta_w^{\frac{1}{4}}(T/T_w)^m(w)^n$$

where C_p = specific heat of air at constant pressure.
η_w = viscosity of air at cylinder well temperature.
T = mean air temperature in cylinder.
T_w = mean well temperature.
w = weight of air passing per sec.

A, m and n are functions of the valve lift, valve area, diameter of cylinder and cylinder length. Average values are:—

$$\left.\begin{matrix} A = 2 \\ m = 1.5 \\ n = 1.0 \end{matrix}\right\} \text{for valves in the cylinder head.}$$

It is stated that the heat transfer calculated with the above coefficient is in agreement with estimates by Neumann and Ricardo.

Heat Transfer from Cylinders having Closely Spaced Fins. (A. E. Bierman, N.A.C.A. Tech. Note No. 602, May, 1937.) (45/52 U.S.A.)

The heat transfer coefficients have been determined for five steel cylinders having fins 1.22 inches wide and the spacing between the fins ranging from 0.022 to 0.131 inch. The cylinders were tested with and without baffles in a wind tunnel; they were also tested enclosed in jackets with the cooling air supplied by a blower. A maximum heat transfer was reached at a fin space of about 0.045 inch for the cylinders tested with each of the three methods of cooling investigated. The rise in temperature of the air passing between the fins and the change in flow pattern were found to be important factors limiting the heat transfer that may be obtained by decreasing the fin space. The use of baffles for directing the air around the cylinders with closely spaced fins proved very effective in increasing the overall heat transfer coefficient provided that the spacing was not appreciably less than that for maximum heat transfer.

High Speed Camera for Propeller Research. (E. L. Gayhart, Engineer, Vol. 164, No. 4251, 2/7/37, pp. 23-4.) (45/53 Great Britain.)

The author describes the experimental camera used at the U.S. naval model basin. The model propeller operates in a glass tank and is illuminated by a photo flash lamp. Single exposures are taken through a rotating shutter (the speed of which is checked by a stroboscope) on a moving film. The exposure rate corresponds to 960 frames a second, the useful duration of the flash generally sufficing for 16 to 17 frames, of which about half are correctly exposed. The model propeller is 8in. diameter and runs at 1,400 r.p.m. (This corresponds to a full-scale destroyer propeller operating at 350 r.p.m.) Examples of photographic records show the formation of tip vortices and the beginning of cavitation.

The Lorenz Blind Landing System Tested in U.S.A. (Inter Avia, No. 433/4, 22/5/37, p. 9; and Les Ailes, No. 838, 8/7/37, p. 9.) (45/54 U.S.A.)

In the course of an examination of the series of accidents by which the American air traffic was characterised at the end of 1936 and the beginning of the current year, the conclusion was arrived at that the U.S.A. might avail themselves of the progressive development of European ground organisation. The Department of Commerce has meanwhile granted large sums for improving the flying safety in the U.S. New evidence of such reforms is furnished by the fact that American air lines are at present carrying out an exhaustive series of tests at Indianapolis with the German Lorenz ultra-short wave blind landing system; Eastern Air Lines and T.W.A. will participate in the experiments. According to a later notice in "Les Ailes," these experiments are now concluded and have demonstrated the superiority of the German system over that put forward by the Air Corps and the Department of Air Commerce. It is the opinion of the French reviewer that the use of the Lorenz system will soon become universal.

Some Problems of Aviation Radio. (F. X. Rettenmeyer, J. Aer. Sci., Vol. 4, No. 7, May, 1937, pp. 297-299.) (45/55 U.S.A.)

The problems discussed include:—

1. Electrostatically shielded loop antenna, to overcome failure of radio communication under certain meteorological conditions (so-called "rain," "snow," or "sand" static).
2. Cone of silence equipment for airport approach (so-called Z marker).
3. Simultaneous reception of weather broadcasts and radio beacon signals.
4. Increase in transmitter output combined with 110-volt supply.
5. Utilisation of short waves so that a multiple purpose receiver can be used for Z markers, radio traffic control and instrument landing.

(Thirty-four references.)

Control of Wireless Signal Variations. (A. L. Green and G. Builder, J. Inst. Elec. Eng., Vol. 80, No. 486, June, 1937, pp. 610-622.) (45/56 Great Britain.)

The paper describes an experimental investigation, for simple conditions of short distance propagation, of fading control of radio signals by methods which rely on transmission being made on adjacent frequencies. It has been found that the frequency separation of the signals required for optimum fading control is determined by the path difference between the ground and sky rays and is independent of the mean frequency of the wave. In general it is necessary to read messages on such circuits by observing the change in direct current in the detector at the receiver, since the audio-frequency components are uncontrolled. Applications of the system of fading control are suggested in connection with ionospheric research, direction finding, and broadcast telegraphy and telephony.

Aerial Navigation by the Valoris Radio Beacon. (Les Ailes, No. 837, 1/7/37, p. 8.) (45/57 France.)

The beacons are arranged in groups of three and transmit of the same wave length, but modulated to three different audio frequencies. Each beacon transmits in turn for $\frac{1}{3}$ sec., the electrical circuit being such as to ensure this accurately, as well as maintaining constant frequency.

The receiving antenna on the aircraft is non-directional, the messages being filtered out and amplified in three circuits tuned to the respective modulations of the three beacons. In this way the field intensity due to each can be measured and thus the distance from each beacon estimated. The field intensity is recorded optically, the locality of the aircraft with respect to the beacons being determined as the centre of a triangular area on a recording dial.

The advantage claimed for this system of navigation is the fact that the aircraft is not tied to a special course as is the case with the usual "homing" devices.

REVIEWS.

Patents for Inventions.

By Reginald Haddan. Published by Sir Isaac Pitman and Sons, Ltd. Price 3/6.

This book describes the British law and practice relating to patents and also includes chapters giving information about patent law in foreign countries and British Dominions and Colonies. It is well and clearly written by an author who obviously knows what he is talking about.

Those who have had to discuss their inventions with ordinary inventors must have been struck with their almost complete ignorance of patent matters and with the curious misconceptions many of them have with regard to patent procedure which is of vital importance if a satisfactory patent is to be obtained. It is too much to hope that this book will reach all such people, but it may be hoped that it will reach many of them. A preliminary reading of this book followed by a consultation with a patent agent when the plans of the invention are complete should ensure satisfactory protection which is a fundamental requisite for commercial exploitation.

The Complete Air Navigator.

By D. C. T. Bennett. Pitman's. 15/-. 1937.

The sound principles of speed, accuracy and common sense, so essential for navigation are emphasised in the preface of this excellent book. And those who never read prefaces will find these principles throughout the book.

The first chapter gives a summary of the mathematical methods necessary in navigation, ending with a summary of formulæ and recommended methods (pp. 38-42). The book is worth buying for these pages alone. Chapters II and IV then give excellent descriptions of maps and wireless D/F. At last someone has treated these subjects from the pilot's viewpoint. We have had books on map projections and books on wireless, written for the cartographer or wireless technician. Mr. Bennett has realised that the pilot or navigator does not wish to construct maps or wireless sets, but is interested in their application. Thus the author emphasises the recognition, properties and uses of various projections. Most books on maps deal very briefly with these. One method of recognition, not mentioned by the author, is to look at the top of the map, where the type of projection is usually given. This method will appeal to the common sense of the author, and to the indulgence of the B Licence candidate. Mr. Bennett has omitted to mention the sinasoidal projection, which is a good thing; but Sir Charles Close's projection, giving distances from two points accurately, say from Botwood and Foynes, should be useful.

The chapters on compasses and dead reckoning are good and practical. The methods of finding the wind are well described, and one gets the impression that the author is speaking from experience.

Astronomical navigation is also well described. Possibly a later edition will give more space to the short methods, particularly to those which are now being developed in this country.

The reader will note that visual time signals are given at many observations. The moment the ball starts to fall is the time required. By noting the time the watch stopped, one can calculate the time required to spin in.

There is only one serious criticism. The subject of meteorology is omitted, without even an excuse. Let us hope that the author will deal with this subject from the pilot's and navigator's point of view in future editions.

FLUID MECHANICS.

By Russell A. Dodge and Milton J. Thompson. Published by McGraw-Hill Publishing Co., Ltd. Price 24/-.

This is an American text-book which contains a large range of matter appertaining to its subject, the range varying from aerodynamical problems to questions concerning lubrication, even corrosion caused by cavitation is discussed. From the aerodynamical point of view the result is unsatisfactory as there is not space for adequate treatment; in fact, the general impression given by the book is that the authors have tried to put more into it than a book of this size can be expected to hold.

Apart from this, the treatment is not always what is expected in a text-book; for instance, the extrapolation of the curve of drag coefficient with Reynolds number is left unexplained, and if ever extrapolation required explanation it is this example. Again, on the second page it is stated that the dimensions of lb. sec.^{2}/ft.$^4 = M/L^3$.

AN INTRODUCTION TO FLUID MECHANICS.

By Alex. H. Jameson, M.Sc., M.Inst.C.E. Published by Longmans, Green and Co. Price 7/6.

This book is intended as a text-book for second year students who propose to take the Part I B.Sc. (Engineering) Examination of the University of London, of which University the author is Emeritus Professor of Civil Engineering.

It should fulfil its purpose admirably. On looking through the book one is immediately struck by the emphasis placed everywhere on dimensional analysis, and the use of examples drawn from aerodynamical problems. When one compares this text-book with those that used to be current on this subject the advance that has been made is striking and the modern student is fortunate in that he has these problems presented to him on the logical basis of the Reynolds number. Students trained with the help of this book and with teaching following the same lines will be much better qualified to deal with the problems they will meet with than their predecessors, who were nurtured mainly on empirical formulæ and tables of coefficients. Further, they will find that the methods they have been taught can be applied to innumerable other subjects which they are likely to meet, for dimensional analysis is a very powerful nut-cracker to those who know how to use it.

THE LAW OF CIVIL AVIATION.

N. H. Moller, M.A., LL.M. Sweet & Maxwell, Ltd. 25/- net.

The law of civil aviation has become an important branch of the law, and will increase in importance during the next few years. The literature on the subject is rapidly assuming formidable proportions, especially as regards the Orders and Regulations which are promulgated under Air Navigation Acts.

Mr. Moller has concentrated on directing attention to the application of general legal principles and analogous cases to those which come within the law of civil aviation. Part I of this comprehensive volume deals with international control of aircraft, statutory control of aircraft, registration and navigation of aircraft and aerodromes, aerial lights and obstructions. Part II covers private rights of airspace, limitation of liability for surface damage, compulsory third-party insurance of aircraft, carriage by air at common law and international carriage by air.

Mr. Moller clears the air in more senses than one in his general exposition of the legal position. There are those who think that aviation either receives special privileges where damage is concerned, or that it is in a peculiar position different from any other form of transport. As Mr. Moller points out, there is nothing exceptional in the insurance of aircraft which alters the application of the usual rules of law as to the interpretation and construction of policies of

insurance. In this section is recalled the disaster to the Tarrant Triplane during its first test flight.

The work under review contains a number of Appendices giving eleven Acts, Conventions and Orders which add to its value, and that they provide easy reference in one volume to the acts concerned.

The Law of Civil Aviation should prove most useful to those who are or may be concerned with legislation on the subject and can be thoroughly recommended.

THE AEROPLANE DIRECTORY OF THE AVIATION AND ALLIED INDUSTRIES.

Temple Press. 10/6.

This Directory gives details of manufacturers and suppliers of aircraft, aero engines, materials and accessories to aircraft in Great Britain; particulars of the various Societies and Clubs in aviation; aerodromes, air transport companies; and aircraft and aero engine manufacturers in the British Dominions, Colonies and Protectorates, and the World.

The work behind such a compilation is immense and arduous, but it is justified by the results. It is a work of very great value to all engaged in the aircraft industry, a mine of information into which one can dig afresh each day and find exactly the data one is looking for, addresses, telephone numbers of firms, aerodromes, clubs, schools and the like. In the aerodrome section full information is given of the facilities available, as well as the nearest railway station, train and hotel. It is typical of the book as a whole. Wherever information is available, that information has been given.

In a directory of this kind there are sure to be a few mistakes and omissions, but a general testing of the contents reveal surprisingly few. Attention is only drawn to one, the omission of Autogiro from the list of Brand and Trade Names.

The Directory should be on the shelves of all those who are concerned with the business side of aviation in any form, whether as manufacturers or as suppliers of aviation parts and accessories.

AIR OVER EDEN.

" N.W." and Sidney Hay. Hutchinson & Co., 1937. 18/- net.

" Air Over Eden " is a travel book. The aim of the authors has been to write a modern air book about Iraq, describing the country or place from the air and adding to it an outline of its history.

The first hundred pages are entirely devoted to a history of Iraq, vividly written, leaving one with powerful impressions of the mysteries and horrors of the East, with, to quote the authors, " the threat of war and the pageantry of peace " in one of the oldest civilisations of mankind.

Towards the end of September, 1936, one of the authors flew a Dragonfly from England to Iraq.

" The direct air route is, however, a practical one, up to a point. That point is Turkey. Civil flying in Turkey is at present neither organised nor seriously encouraged. Aerodromes are badly marked. Intermediate landing grounds are few and far between. Meteorological information is untrustworthy. At one aerodrome enquiries, after particularly bad weather, elicited the information that the individual responsible for sending weather reports had been away for a week, but had left behind him a series of assorted telegrams to suit all tastes!"

In Turkey the authors " stayed in a local hotel where the manager sought to get rich much too quick." A whole page of description of the hotel is contained in that brief sentence! Again " we first visited the shops (in Aleppo) in a car with chains on the wheels, and bought two cooked chickens, some bread (of which we only dare eat the middle owing to the swarms of flies which had settled on the crust)."

In Jerusalem, they were reminded of, despite its serious associations, the ribald reply of a Lancashire man. His friend claimed that his battalion was the first to

enter the town in the Palestine campaign. " Ba gum, lad," said the Lancastrian, " ah reckon t' blinkin' shepherds watched their flocks that neeght!"

Here is the other side, of a search for missing slaves.

" The officer strolled about the courtyard. Suddenly an idea struck him. Calling his men, he bade them tear down one of the newly cemented blocked-up archways. Inside was a Somali slave. He had been buried alive. That house is now the residence of the political agent. The other arches remain cemented."

A tale is told of a lady who was walking along Ar-Rashid Street in Baghdad when she saw a fine bull terrier in the back seat of a car drawn up near the Maude Bridge. A lover of animals, she could not resist stopping to pat him, saying:

" You perfect darling."

" Who?" said the young air force officer at the back, " Me, or the dog?"

" Air Over Eden " is full of stories, deft descriptions, and keen observation from the air and the ground which makes it one of the most lively and informative books of its kind, and a real pleasure to read.

ROBERT GSELL: " 25 JAHRE LUFTKUTSCHER " (25 YEARS OF PILOTING AIRCRAFT). 256 pages with 32 photos. Published by Eugen Rentsch, Erlenbach-Zuerich (Switzerland). Price 4.70 R.M.

Robert Gsell, Technical Chief of the Swiss Federal Air Office—dreaded by crashing pilots and " thorn in the flesh " of naughty aeroplane constructors—is certainly one of the most remarkable personalities in aeronautics. He is not only a first class engineer, but one of the finest pilots in the world, and he handles sailplanes, autogiros, airships and free balloons as well as normal aeroplanes of every description.

Gsell learned to fly early in 1911 at the Blèriot School at Pau by means of the " hop-and-crash " method and became shortly afterwards an excellent test pilot for land and seaplanes in Germany. He was assistant to Prof. H. Reissner in full-scale research work with tail first metal monoplanes and airscrews with hinged blades (during 1913), helped in design and did all flying of Friedrichshafen seaplanes up to the beginning of the war. During the war Gsell acted as a works manager in a German aircraft factory, facing all war time production difficulties, and finished then in Germany as a principal scientific officer to the German Research Institute for Aeronautics.

Gsell met every kind of accident in the air—from buckling up wing spars and disintegrating front elevators to joysticks becoming unexpectedly disconnected in flight—and he is still going strong at the controls. There is no type of flying vehicle registered in Switzerland which has not been passed out for safe flying qualities by his able hands. He is a military pilot and an expert in military flying as well, in spite of being, physically, utterly unacceptable for any reasonable air force in the world; unfortunately he has lost the sight of one eye in early youth, and he is also short-sighted. His deductions (p. 74) with regard to the importance of stereoscopic view and parallaxis in flying especially in alighting with seaplanes on oily sea therefore deserve a very careful consideration by medically interested air people.

In life Gsell is a great humorist indeed, and that seems no wonder after all the incidents and accidents he has had to go through. His log book reflects some of his true spirit and gives more than only thrill and adventure; there is the spirit of the flying pioneers of 25 years ago in it, a lot of advice gained in so many years of handling aircraft and wise comments regarding the human side of flying.

Following a fall out of a window in early youth—Mr. Gsell reports—the doctors came to the conclusion that either he would not survive or he would become an idiot for life. The book is the best proof that this medical opinion is rather exaggerated. The world needs more of this sort of should-be-idiots anyway.

CORRESPONDENCE.

Aeroplane Stability and the Automatic Pilot.

Note.—The following was inadvertently omitted from the June Journal.—Ed.)

To the Editor of the Journal of the Royal Aeronautical Society.

Sir,—I suggest that a detailed weight schedule of both the R.A.E. and Sperry types might be included in the published paper so that designers could assess their respective merits. The Sperry device had been cited as 60lb. by the makers, although I believe that an installed figure of 100lb. is generally specified by the U.S. Department of Commerce. I understand that the authors' gear was considerably heavier than the Sperry, but it would undoubtedly enlarge the interest of the paper to have the official figures broken down into reasonable detail. Could the authors tabulate the weights for a few typical installations, since there must be plenty of such data available?

I am not quite clear just what the authors intended to convey by the statement under Lateral Stability that:—" Were the dihedral effect removed—this would require a slight negative dihedral—etc." In view of recent research on tapered wings, both at the R.A.E. and the N.P.L., I understand that the question of effective dihedral was powerfully influenced by plan-form effects, such as sweep-back and sweep-forward of the trailing edge. Thus, a pronounced forward sweep of the trailing edge had been shown to negative the effect of a 5° positive geometric dihedral on a 4 : 1 taper, hence the true aerodynamic dihedral was approximately zero. (Sweep-back, on the other hand, was itself equivalent to a certain degree of dihedral varying with the angle of incidence.) The deleterious effect of sweep-forward on dihedral seemed to be the reverse of that stated in the paper. Were the authors thinking in terms of the rectangular wing?

Yours, etc.,

S. H. Evans (*Member and Associate Fellow*).

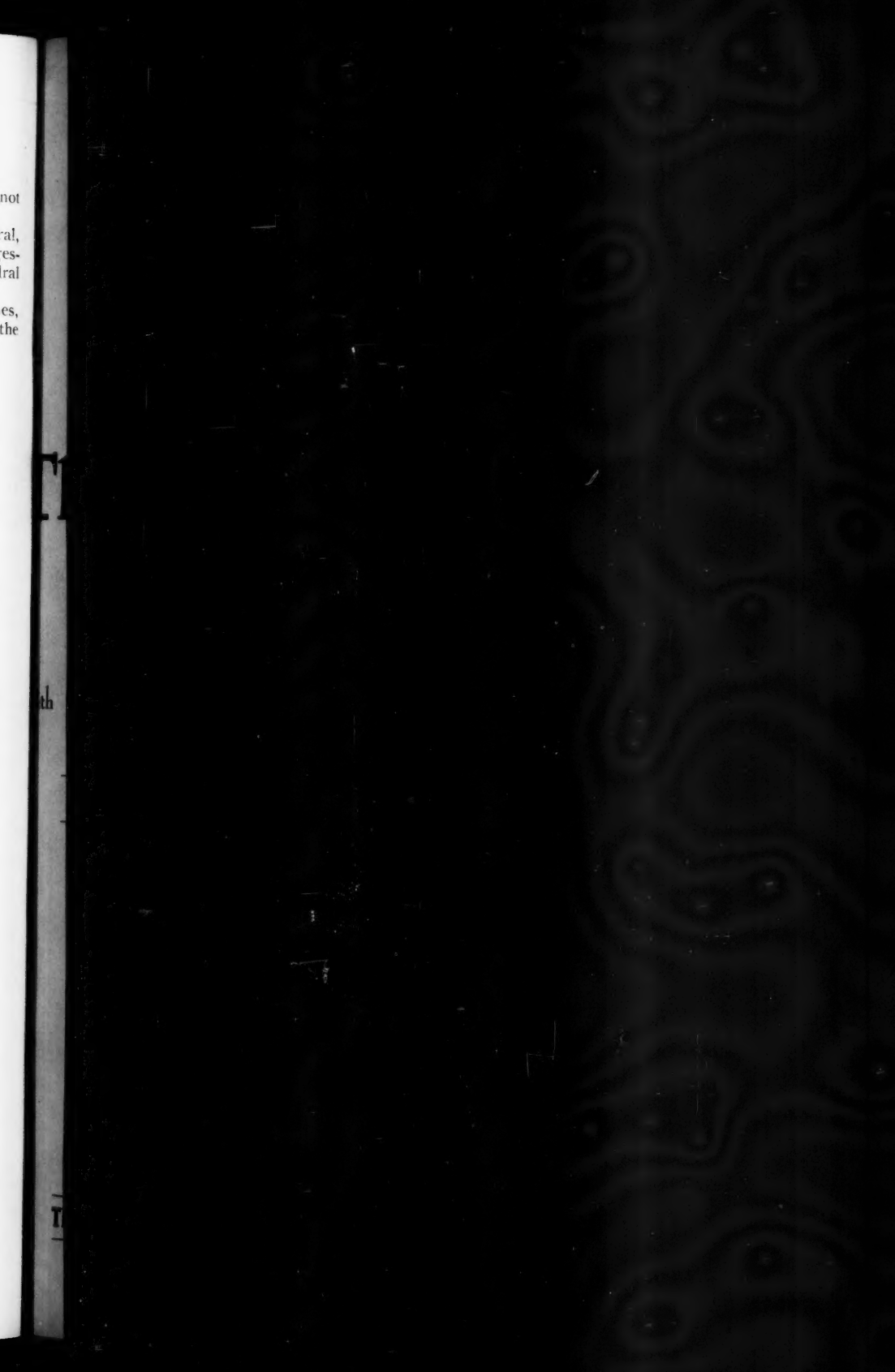
Sir,—I should like to emphasise the importance of weights and similar data because when operators went into this question of the automatic pilot, they were asked what it was going to cost, not only its initial cost, but the complications that arose from the operator's point of view, which were very considerable. I know, by the way, of at least one British automatic pilot, not yet, I think, fully developed which is exceedingly promising from this point of view. About three years ago I met Captain Bailey at Croydon Aerodrome at a time when I knew as little about automatic pilots as I do now, and Captain Bailey asked me whether I would like to see how the automatic pilot worked. I believe that he was then experimenting with his first three-axes device, there was a previous two-axes. At 4,000ft. he said, " Now we switch over." The P.B. automatic pilot weighed about 45lbs. when installed, and there were no complicated gadgets necessary for getting into the fuselage as there were in certain American pilots. I remember reading of one which Wiley Post had intended to use in his stratosphere flights which was a most complicated affair, weighing 65lbs. Could the authors give comparative weights, and also could they say whether within the next two years an automatic pilot might be expected, more or less foolproof, and no more than 45lbs. in weight, and not interfering seriously with the ordinary controls of the aeroplane?

Yours, etc.,

Farey Jones.

Reply from Mr. Meredith.

Mr. Evans raises a question in regard to effective dihedral which was not answered at the meeting because the authors had not heard the question.

The authors had not intended to be abstruse on the question of effective dihedral, but merely to point out that it was not identical with actual dihedral. The suggestion that removal of the dihedral effect would require a slight negative dihedral referred, as Mr. Evans surmised, to substantially rectangular wings.

In reply to Mr. Evans' question about weights, also raised by Mr. Farey Jones, I must refer them to page 436 of the Journal, where I state in general terms the difficulty of giving specific weights.